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DEVELOPMENT OF SOILS ON CALCAREOUS QUARRY DETRITUS OF OPEN-PIT OIL-SHALE MINING DURING THREE DECADES

Loit REINTAM[a] and Elmar KAAR[b]

[a] Institute of Soil Science and Agrochemistry, Estonian Agricultural University, Viljandi mnt., Eerika, 51014 Tartu, Estonia
[b] Forest Research Institute, Estonian Agricultural University, Kreutzwaldi 5, 51014 Tartu, Estonia

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Abstract. Primary pedogenesis on quarry detritus under planted stands was studied in six experimental areas at Kohtla and Viivikonna, North-East Estonia. During 29–35 years, natural differentiated soil sections have formed. These were classified as Calcaric Regosols and Calcaric Arenosols. Both represent an output of a highly intensive production process. Besides the root system, ground forest litter of the *Moder* and/or *Mull*-like *Moder* type was the main pedogenetic agent there. Although some residues of kukersite could humify and participate in the formation of the epipedon close to mollic, the composition of humus demonstrates the crucial role of plant remains in the humification processes during the progress of soils. Humus formations from humic-fulvic to humic are rich in organic carbon, but poor in nitrogen and free fulvic acids, and are mainly bound with mobile sesquioxides. Humus is characterized by a large proportion of insoluble residue. Therefore, pedogenetic argillization was extremely weak and humus colloids were prevalent in the soil exchange complex. Exchangeable hydrogen was completely lacking, soil reaction was alkaline. Changes in iron relationships reveal a slight formation of cambic properties in some soil sections.

Key words: primary pedogenesis, soils on quarry detritus, humus and iron relationships.

INTRODUCTION

Soil formation on top of any kind of weathering crust can start after the formation of a plant cover and beginning of organic-mineral interactions. Different tills and aqueous deposits are the main mineral resources for soil processes in glacial areas. Crystalline basement and/or paleozoic, mesozoic, etc.

rocks can serve as initial material for soils on their local territorial outcrops. Quarry detritus of any texture and structure, formed in the process of open-pit mining from the rocky mantle, overlying mined mineral wealth, represents one of the natural parent materials for the development of soils. Since the open-pit technique, applied in commercial mining, has been largely available only during about a century and the duration of the subsequent impact of vegetation and the produced organic matter on mineral strata is usually dated, changes in quarry detritus characterize not only the progress of plant–stratum interactions but also the trends and rates of contemporary pedogenesis there (Schafer et al., 1980; McSweeney & Jansen, 1984; Uzhegova & Makhonina, 1984; Roberts et al., 1988a, b).

In connection with intensive rehabilitation of the highly skeletal calcareous detritus of oil-shale mining (Photo 1) for the forestry in North-East Estonia, Vaus (1970) summarized the database of the silvicultural properties of detritus studied and used for forest planting. Besides, the natural development of the plant cover as well as the technique and results of rehabilitation were characterized (Kaar et al., 1971). As it was prognosticated already in the early 1960s, afforestation of quarry detritus with 2–3 year sets proved to be highly effective. Normally functioning forest ecosystems developed everywhere. Within

Photo 1. Levelled quarry detritus before afforestation in North-East Estonia in the early 1960s. Photo by E. Kaar.

some decades they were subjected to visual qualitative observation, and selective sampling of tree constituents and forest litter formed was carried out in some areas. To ascertain the character and capacity of pedogenesis, the soils formed on pure detritus during 29–35 years were sampled in 1996. The age of young soils studied there is close to that of soils formed in the course of a special experiment conducted on reddish-brown calcareous till under only herbaceous vegetation (Reintam, 1995, 1997, 1998) as well as on sandy loam deposit under oak and pine (Graham et al., 1995). The aim of this paper is to characterize the development of forest soils and their properties under stands that have developed from sets synchronously with the formation and development of the entire forest–soil system.

MATERIAL AND METHODS

Sites, sampling, and taxation

Four areas at Kohtla (27°08′E, 59°21′N) and two areas at Viivikonna (27°45′E, 59°19′N) were investigated within forest compartments 77 and 81, and 69, respectively. Afforestation of skeletal quarry detritus with the average content of fractions >10 mm 68.8% at Kohtla and 63.5% at Viivikonna, and with the coefficient of variance 22–27% (Vaus, 1970) was carried out in 1963–67. Two-year sets of Scotch pine (*Pinus sylvestris*) and silver birch (*Betula pendula*) and three-year sets of larch (*Larix europaea*), maple (*Acer platanoides*), oak (*Quercus robur*), and lime-tree (*Tilia cordata*) were used. The development of ground layers as well as underwood took place in a natural way. During 29–35 years no human impact has occurred on stocking density and canopy structure.

The morphological description and soil sampling by the genetic horizons formed were carried out in October 1996 to a depth where signs of pedogenesis occurred and/or where digging was feasible owing to high stoniness of the parent material. Well known methods of soil science were applied (Soil Survey..., 1996). Stand taxation was carried out in circular areas of 0.1 ha each in October 1998. The obtained data are presented in Table 1. However, owing to the use of 2–3-year sets and a 2-year interval between soil sampling and forest taxation, tree age is four years higher for pine and birch, and five years higher for larch, maple, and lime-tree compared with the real duration of pedogenesis before soil sampling. The development of soil properties as shown in the following tables could have taken place in the space of time from afforestation of detritus with the use of sets up to sampling in 1996. That is why data for stand age in Table 1 differ from those in the other tables. A series of data on forest litter and thin epipedon were collected and analysed by Elmar Kaar in 1986/87. These unpublished materials were partly used in this paper.

Table 1. Taxation characteristics of stands

Area	Composition*	Trees	Age	Stocking density	Average height, m	Breast-height diameter, cm	Number of trees per ha	Breast-height basal area, m^2 ha^{-1}	Growing stock, m^3 ha^{-1}
Kohtla 77/28	10B+M	Birch ns	32	1.0	17.2	13.7	1446	21.4	178
	2nd layer	Maple	38	0.4	8.9	8.8	1302	7.9	40
		Limetree	38	0.0	8.2	7.2	83	0.3	2
Kohtla 77/24	7L 3P	Larch	38	0.7	18.2	21.1	680	23.8	205
		Pine	37	0.2	15.2	17.5	300	7.2	54
	2nd layer	Spruce	39	0.3	11.0	10.6	1100	9.6	57
Kohtla 81/20	10B	Birch	34	1.1	17.8	13.0	2050	26.7	228
81/19	10P+B	Pine	34	0.9	13.3	13.2	2000	27.4	185
		Birch ns	29	0.05	16.6	13.4	70	1.0	8
Viivikonna 69/8	10P	Pine	38	0.9	17.7	15.1	1850	33.3	280
69/14	7P 3B	Pine	40	0.5	15.8	15.4	860	16.0	123
		Birch ns	35	0.3	18.2	19.0	280	7.9	69

* B – silver birch, planted; B ns – silver birch, natural spontaneous; L – larch; M – maple; P – Scotch pine.

Analysis

Analyses were performed by the research assistant Mrs. Raja Kährik at the laboratories of the Institute of Soil Science and Agrochemistry, Estonian Agricultural University. Fine earth of less than 2 mm particle size was used. 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. Carbonates were determined acidometrically with 0.1 M HCl.

The group and fractional composition of humus was determined by an alternate acid–alkaline treatment using the Tyurin–Ponomareva volumetric method (Ponomareva, 1957). The results obtained were expressed in percentages of organic carbon. Total percentages of organic carbon and nitrogen were ascertained by the Tyurin and Kjeldahl methods, respectively. Nonsiliceous iron was determined after Coffin, amorphous sesquioxides and silica after Tamm, and iron activity after Schwertmann (Zonn, 1982). Base exchange capacity (BEC) and exchangeable bases were measured by percolation of a sample with ammonium acetate at pH 7.0. The pH values of water and 1.0 M KCl suspensions were determined potentiometrically with a glass electrode.

Weighed raw samples of ground litter were fractioned by their main constituents, dried at 105 °C, and weighed again after cooling. On the basis of the obtained data, the total raw mass of fractions was recalculated as dry mass. For chemical analysis, fractions were again mixed and milled. Milled dry material was used both for dry combustion and wet digestion techniques. Total ash was ascertained by the method of dry combustion at 600 °C. Nitrogen, phosphorus, and potassium were determined by the method of wet digestion with concentrated sulphuric acid after Kjeldahl, photocolorimetrically with ammonium vanadate, and with the help of flame photometry, respectively (Rodin et al., 1968). The group and fractional composition of humus were determined as described above.

Analyses made in 1986/87 at the laboratories of the former Estonian Research Institute of Forestry and Nature Conservation were performed by the same methods.

RESULTS AND DISCUSSION

High productivity stands (Photos 2–4) were formed during about three decades (Table 1). According to their growing stock they are close to the highest quality natural forests of the goutweed site type (Etverk et al., 1995). Compared with the status of 1965–68 (Vaus, 1970; Kaar et al., 1971), an about up to eightfold increase in the total height and up to fivefold increase in the breast-height diameter has occurred. The average annual increment of the growing stock is estimated at 5.7–8.5 solid metres per hectare. In some areas, spontaneous appearance of silver birch is the result of natural afforestation even in the first layer. A normal grass–herbaceous cover with a density higher than 0.7 is characteristic of most sites. Green mosses (including *Rhytidiadelphus triquetrus*) prevail in the ground vegetation only under larch and pine stands. During the first decade young pine stands did not yet coalesce and a thin ground litter formed only under tree crowns. Simultaneously with an increase in pine coalescence, a steady forest floor with a depth of 2–3 cm and a mass of 2.7–3.6 kg m^{-2} formed under stands during 20–25 years. Its top represented ground litter consisting of needles and herb and moss residues. The lower part was a poorly decomposed forest floor where the origin of aboveground plant residues was easily recognizable.

The formation of a permanent forest floor tends to be the main prerequisite for further accumulation of moisture as well as for intensification of litter decomposition and development of interactions between organic agents and the mineral stratum during the last decade, i.e. from 1986 to 1996. About half of the

Photo 2. A larch–pine stand at Kohtla in 1998 with thick-covered spontaneous grass-herbaceous sward in the forefront. Photo by L. Reintam.

pine litter consisted already of decomposed material (Table 2) whose initial origin has changed beyond recognition. Some 40% of this litter were needles of several recent falls. Owing to prevalent autumnal litter fall in deciduous stands, the percentage of decomposed material was lower there, while that of changed leaves and wood was higher. As a result of more intensive mineralization of leaves compared with needles (Arvisto, 1971), the current increment of fermented and/or humified litter as well as its stock must be and indeed is smaller in any deciduous forest (Kylli, 1986). That is why the thickness of the forest floor tends to be stabilized in the limits of 2–3 cm under birch stands but has increased up to 5 cm under the pine stands at Viivikonna.

Ten years ago, the ashness of the forest floor under pine stands was 37–51% (42.4% as an average of 94 samples). The nearly twofold decrease in ash during the last decade (Table 2) cannot be associated with temporal changes in biogeochemical cycling. Rather, the reason is isolation of litter from underlying

Photo 3. A silver birch stand of high quality at Kohtla in 1998. Photo by L. Reintam.

strata within the process of stabilization of ground litter/forest floor protected from atmospheric dust by the progress of forest coalescence. The relatively low ashness of the deciduous ground litter can be due to rapid mineralization of leaves and translocation of mobilized ash elements back into the solum without *in situ* formation of secondary complexes. The nitrogen and potassium contents (Table 2) were nearly at the same level as in 1986 (1.04 and 0.23%, respectively), being slightly smaller in pine stands at Viivikonna than elsewhere. The phosphorus content was everywhere <0.1% in 1986. A significant increase in the participitation of phosphorus in biological turnover (Table 2) seems to be connected with the intensified impact of humus substances on the detritus stratum relatively rich in phosphorus. Its mobilization before the attainment of forest coalescence was probably inhibited due to the insufficient amount of organic agents.

Primary pedogenesis on skeletal and/or sandy detritus is humus-accumulative in its origin (Tables 3 and 4). The epipedon on skeletal material at Kohtla (Table 3) is sufficiently dark, base saturated and rich in organic carbon, but too thin (less than 5 cm) to be exactly mollic. The only exception is the epipedon under birch and maple stands where a deep humous mollic epipedon has formed during 32 years. In spite of this, all soils at Kohtla seem to be Calcaric Regosols rather than Rendzic Leptosols (FAO–UNESCO, 1997); their taxonomical belonging needs

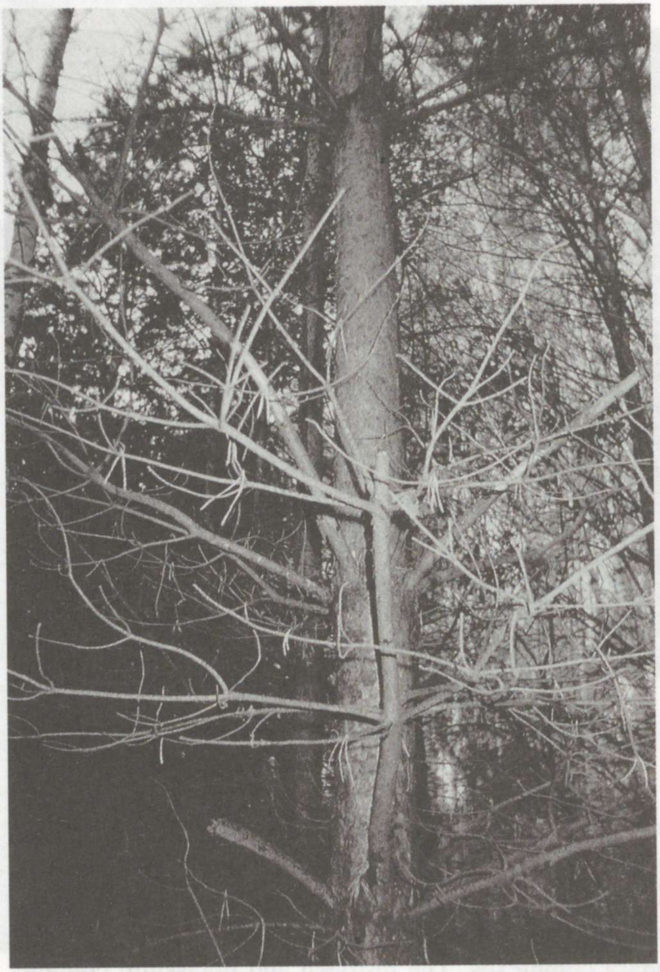

Photo 4. Natural lopping of Scotch pine was weak in a dense high productivity stand at Kohtla in 1998. Photo by L. Reintam.

special discussion since it can change in the process of further development. A deep (at least 20 cm), dark, base saturated and humous epipedon, close to mollic, has been forming under pine stands on sandy detritus at Viivikonna already during 33–35 years (Table 4). These soils are not Leptosols, but they are too sandy to be identified as Regosols. Therefore, they are referred to as Calcaric Arenosols here. The formation of humus rich in carbon but poor in nitrogen, and its accumulation in the 5–30 cm top layer of detritus are characteristic of the humus-accumulative process in both cases. Vaus (1970) suggested that quarry detritus, levelled for afforestation, contains small pieces of broken oil shale owing to which on average 2.3% of organic carbon exists there already before the beginning of forest–soil interactions. According to Fomina et al. (1965), oil shale (kukersite) will be easily subjected to the physical weathering and oxidation in the composition of aerated detritus. These phenomena lead to the separation of water, CO, and CO_2, and humification of kukersite.

Table 2. Fractional and chemical composition of forest litter (%) in 1996

Fractions	Kohtla 77/28 Birch–maple	Kohtla 81/20 Birch	Kohtla 81/19 Pine	Viivikonna 69/8 Pine	Viivikonna 69/14 Pine (birch)
Root residues	6	3	2	4	0
Wood pieces	10	6	5	2	9
Changed wood and leaves	48	65	2	8	6
Needles	0	0	36	40	37
Decomposed material	36	26	55	46	48
Depth, cm	2	3	3	5	5
Stock, kg m^{-1}	2.4	3.6	3.6	6.0	6.0
Ashness	20.3	17.3	22.3	34.4	21.7
Organic C	31.54	33.12	30.22	24.37	25.49
N	1.40	1.31	1.35	1.14	0.97
C : N	22.5	25.3	22.4	21.4	26.3
P	0.24	0.28	0.23	0.26	0.27
K	0.18	0.19	0.17	0.18	0.12

It seems likely that dispersed kukersite that has remained in the composition of detritus tends to oxidize and transform into simple oxides. Conditions for this process were especially favourable during the first two decades after planting when the surface was open to atmospheric hydrothermal impact on the stratum. Both gas volatilizion and solution could induce losses of organic carbon. Considering the suggestion of Fomina et al. (1965), the appearance of resynthesized humic formations on the account of insoluble residues of kukersite cannot be excluded either. Thus, the high content of organic carbon (6.6–16.6%) in the 5–10 cm layer directly underneath the forest floor, as well as the fulvic–humic or fulvic composition of humus, are results of both the chemical oxidation of residual kukersite pieces and pedogenetic processes during about three decades. The latter processes seem to be prevalent everywhere.

A low degree of humification (<10% humic acids) and obvious fulvicity (by low humic:fulvic ratio) are characteristic of humus in Calcaric Regosols (Table 3) where kukersite in parent detritus revealed higher than average values (Vaus, 1970). On the contrary, Calcaric Arenosols on sandy quarry detritus poor in kukersite are characterized by fulvic–humic and/or humic humus whose degree of humification is about twice as high (Table 4). Such a situation would be hardly possible if the oxidation products of kukersite were predominant in accumulated humus. A high C:N ratio (>20) in all soils demonstrates that nitrogen bridges in the polyphenolic molecules of humus substances are still weak, and humus is not yet mature. This phenomenon in its turn could substantiate

Table 3. Humus composition of thin Calcaric Regosols (% of organic carbon) on open-pit quarry detritus at Kohtla

Characteristics	Birch and maple stand (32 years)		Larch and pine stand (34 years)		Birch stand (29 years)	Pine stand (29 years)
	A 0–10 cm	A 18–23 cm	A 0–3 cm	AC 3–5 cm	A 0–5 cm	A 0–5 cm
Org. C, % of soil	16.16	9.42	16.61	0.88	7.73	8.06
Total N, % of soil	0.45	0.32	0.39	0.10	0.25	0.28
C : N	35.9	29.4	42.6	8.8	30.9	28.8
Humic acids (H.a.)						
1	2.4	3.0	5.7	6.8	2.2	3.1
2	1.9	0.3	1.2	1.2	0.8	1.6
3	1.1	6.1	1.1	3.4	2.2	2.4
Σ	5.4	9.4	8.0	11.4	5.2	7.1
Fulvic acids (F.a.)						
1a	2.2	2.4	3.8	12.5	2.1	2.5
1	3.7	1.6	10.6	13.6	4.0	4.7
2	6.8	2.8	5.3	14.8	1.8	6.2
3	2.3	4.3	1.4	4.6	2.7	1.7
Σ	15.0	11.1	21.1	45.5	10.6	15.1
0.5 M H_2SO_4 hydrolysate	3.4	6.1	4.4	13.6	5.7	3.7
Total soluble	23.8	26.6	33.5	70.5	21.5	25.9
Insoluble	76.2	73.4	66.5	29.5	78.5	74.1
H.a. : F.a.	0.36	0.85	0.38	0.25	0.49	0.47
1st fr. : 2nd fr.	0.70	1.48	2.53	1.29	2.40	1.00
Decalcinate, % of soil						
Fe	0.46	0.31	0.81	0.17	0.46	0.60
Al	0.22	0.37	0.08	0.18	0.06	0.10
Ca	0.11	0.08	0.03	0.01	0.06	0.02
Mg	0.02	0.01	0.01	0.00	0.01	0.01

a certain participation of oxidized kukersite in the humus formed during pedogenesis. Since a high C:N ratio (27–29) characterized forest litter as a natural contemporary source for humification and a direct agent for pedogenesis already a decade ago, the formation of humus rich in carbon and poor in nitrogen can be expected there. Although the share of nitrogen has increased and the C:N ratio for forest litter has become narrower (Table 2), no basic changes occurred in the maturity of litter humus during the last decade. A large portion of insoluble residue can be interpreted both as transformation of kukersite mixture in detritus and as rapid humification of plant remains in seasonally arid calcareous conditions. Except for Regosol under the larch–pine stand, fixation of

Table 4. Humus composition of Calcaric Arenosols (% of organic carbon) on open-pit quarry detritus at Viivikonna

Characteristics	Pine stand (33 years)		Pine stand (35 years)		
	A 0–10 cm	AC 10–20 cm	A 0–10 cm	A 10–20 cm	AC 20–30 cm
Organic C, % of soil	3.15	3.68	6.63	4.97	2.75
Total N, % of soil	0.16	0.10	0.29	0.24	0.10
C : N	19.7	36.8	22.9	20.7	27.5
Humic acids (H.a.)					
1	10.2	5.4	10.4	10.9	4.7
2	6.0	0.9	0.4	0.2	0.8
3	2.5	2.7	7.8	11.4	12.7
Σ	18.7	9.0	18.6	22.5	18.2
Fulvic acids (F.a.)					
1a	3.8	2.4	2.6	2.8	2.9
1	8.3	2.7	3.1	6.2	1.4
2	9.8	5.5	6.3	5.9	5.1
3	2.9	2.2	4.7	8.5	1.8
Σ	24.8	12.8	16.7	23.4	11.2
0.5 M H_2SO_4 hydrolysate	4.8	4.3	6.8	7.0	10.2
Total soluble	48.3	26.1	42.1	52.9	39.6
Insoluble	51.7	73.9	57.9	47.1	60.4
H.a. : F.a.	0.76	0.70	1.11	0.97	1.61
1st fr. : 2nd fr.	1.16	1.30	2.05	2.83	1.06
Decalcinate, % of soil					
Fe	0.21	0.23	0.22	0.21	0.15
Al	0.16	0.07	0.03	0.01	0.13
Ca	0.02	0.03	0.05	0.04	0.04
Mg	0.01	0.00	0.01	0.01	0.01

Table 5. Texture of Calcaric Regosols (%) at Kohtla

Fractions, mm	Birch and maple stand (32 years)		Larch and pine stand (34 years)		Birch stand (29 years)	Pine stand (29 years)
	A 0–10 cm	A 18–23 cm	A 0–3 cm	AC 3–5 cm	A 0–5 cm	A 0–5 cm
2–0.5	2.0	2.3	3.9	2.6	7.7	9.6
0.5–0.25	10.1	12.6	16.8	9.9	22.0	15.5
0.25–0.1	20.1	20.4	40.2	42.7	17.2	17.3
0.1–0.05	11.8	12.7	16.0	15.4	11.8	15.1
0.05–0.02	13.1	15.0	9.3	7.9	12.7	13.6
0.02–0.005	17.7	16.4	6.3	6.8	13.3	14.5
0.005–0.002	7.6	5.3	1.0	2.3	3.6	3.2
<0.002	17.6	15.3	6.5	12.4	11.7	11.2

Table 6. Texture of Calcaric Arenosols (%) at Viivikonna

Fractions, mm	Pine stand (33 years)			Pine stand (35 years)			
	A 0–10 cm	AC 10–20 cm	C 25–35 cm	A 0–10 cm	A 10–20 cm	AC 20–30 cm	C 30–35 cm
2–0.5	9.9	8.3	9.1	15.5	10.6	13.0	6.5
0.5–0.25	24.5	33.5	17.7	19.6	23.5	16.4	17.2
0.25–0.1	30.4	26.6	22.5	26.3	21.8	22.2	21.8
0.1–0.05	12.0	8.9	16.5	11.7	8.7	12.3	16.2
0.05–0.02	7.0	9.2	9.2	6.4	12.6	13.7	11.5
0.02–0.005	8.3	6.8	14.4	11.6	13.1	14.8	15.9
0.005–0.002	2.8	1.3	3.7	2.4	2.8	2.0	3.5
<0.002	5.1	5.4	6.9	6.5	6.9	5.6	7.4

Table 7. Physico-chemical and chemical properties of Calcaric Regosols at Kohtla

Characteristics		Birch and maple stand (32 years)		Larch and pine stand (34 years)		Birch stand (29 years)	Pine stand (29 years)
		A 0–10 cm	A 18–23 cm	A 0–3 cm	AC 3–5 cm	A 0–5 cm	A 0–5 cm
pH of H_2O suspension		7.6	7.6	6.5	7.2	7.6	7.5
pH of 1 M KCl suspension		7.1	7.1	6.2	6.8	7.1	7.1
BEC, cmol kg^{-1}		29.9	24.9	32.9	5.4	18.0	18.1
Exchangeable	Ca	26.3	22.5	24.0	4.3	16.2	16.2
	Mg	3.2	2.1	6.2	0.9	1.4	1.5
	K	0.3	0.2	1.5	0.2	0.3	0.3
	Na	0.1	0.1	0.2	0.0	0.1	0.1
$CaCO_3$, %		16.8	17.4	2.4	1.3	13.2	13.2
Total nonsiliceous Fe, %		1.13	1.30	0.59	0.29	0.82	0.68
Amorphous (%)	Fe	0.43	0.50	0.30	0.15	0.36	0.35
	Al	0.08	0.08	0.30	0.08	0.09	0.08
	Si	0.12	0.05	0.11	0.09	0.10	0.11
Fe-activity, %		38.1	38.5	50.8	51.7	43.9	51.5

fulvic acids seems to be quite complete. Therefore the presence of free fulvic acids (1a fraction) is insignificant (Tables 3 and 4), as a result of which pedogenetic argillization (Tables 5 and 6) is weak and the calcareousness (Tables 7 and 8) of soil sections appears to be relatively stable.

Humic–fulvic complexes bound with mobile sesquioxides (especially with iron) prevail over those bound with alkaline earths (Tables 3 and 4). The only exception is the top of Regosol under birch and maple. Mobilization of sesquioxides, formation and accumulation of R_2O_3-humates as well as fulvates bound with the latter confirms the pedogenetic origin of soluble humus. If some part of it had formed as a result of kukersite oxidation, the predominance of

Table 8. Physico-chemical and chemical properties of Calcaric Arenosols at Viivikonna

Characteristics	Pine stand (33 years)			Pine stand (35 years)			
	A 0–10 cm	AC 10–20 cm	C 25–35 cm	A 0–10 cm	A 10–20 cm	AC 20–30 cm	C 30–35 cm
pH of H_2O suspension	7.4	7.6	7.7	7.6	7.6	7.7	7.7
pH of 1 M KCl suspension	7.0	7.1	7.3	7.1	7.1	7.2	7.3
BEC, cmol kg^{-1}	8.7	7.7	4.9	24.4	22.6	8.3	8.0
Exchangeable Ca	7.1	6.8	4.4	21.7	20.5	7.1	6.7
Mg	1.5	0.8	0.4	2.4	1.9	1.1	1.2
K	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Na	0.04	0.03	0.03	0.1	0.1	0.04	0.04
$CaCO_3$, %	8.3	9.7	14.6	15.1	15.6	16.9	16.9
Total nonsiliceous Fe, %	0.32	0.41	0.56	0.56	0.53	0.49	0.54
Amorphous (%) Fe	0.18	0.41	0.39	0.34	0.34	0.34	0.30
Al	0.05	0.08	0.05	0.09	0.10	0.06	0.06
Si	0.08	0.14	0.07	0.09	0.25	0.11	0.16
Fe-activity, %	56.3	100.0	69.6	60.7	64.2	69.4	55.6

Ca(Mg)-humic–fulvic complexes would have been evident. However, the role of magnesium in the fixation of humus acids is insufficient or lacking altogether. Unlike in case of primary pedogenesis on calcareous till (Reintam, 1995), only a small portion of fulvic acids (extracted by 0.5 M sulphuric acid) was bound in the structure of secondary minerals here.

Textural differentiation of pedogenetic origin on quarry detritus was extremely weak during three decades (Tables 5 and 6). A tendency of breakdown of sand particles and a slight accumulation of silt particles can be found characteristic of organic–mineral interactions that have taken place, while changes in carbonate sand and gravel seem most important. Synthesis and accumulation of secondary clay were not yet established there. This is one of the principal differences between primary pedogenesis on calcareous-alumosiliceous till (Reintam, 1997) and skeletal coarse quarry detritus. Against the background of only slight argillization the main role in the genesis of the colloidal complex is played by humus substances and by organo-mineral formations (Tables 3, 4, 7, and 8). The higher the humousness, the greater is the BEC. At the same time, the composition of exchangeable bases seems to be dependent upon carbonates and upon the dynamics of their transformation. When released, calcium and magnesium are involved in the fixation on humus colloids (Tables 7 and 8). Because of rapid neutralization of fulvic acids, formation of saturated humic–fulvic complexes, and a negligible amount of free fulvic acids, all the studied soils are characterized by alkaline reaction and absence of exchangeable acidity.

As a result of weathering, oxidation, and pedogenetic interactions, mobilization of nonsiliceous iron was quite significant not only in epipedons, but also in the uppermost part of parent detritus (Tables 7 and 8). The process was especially noteworthy at Viivikonna under pine stands on sandy material. The accumulation of amorphous iron and an increase in iron activity at the interface of the epipedon and the parent material can be interpreted as the first sign of the development of cambic properties there. The amount of total nonsiliceous iron is greater, whereas iron activity is lower under deciduous stands (Table 7). It is possible that vigorous transformation of leaves litter and more intensive turnover of substances there favour the crystallization of amorphous compounds in the conditions of improved aeration. Aluminium mobilization was highly insignificant. The only exception was Regosol under larch and pine where fulvicity and the content of free fulvic acids were also much higher than elsewhere (Table 3).

CONCLUSIONS

During 29–35 years thin humus-accumulative soil sections were formed on quarry detritus under planted forests whose average annual increment in the growing stock was 5.7–8.5 solid metres per hectare. The ground litter of the *Moder* and/or even *Mull*-like *Moder* type (*mullartiger Moder* after Kubiena cited in Müller, 1980) with the C:N ratio 21–26 is characteristic of both Calcaric Regosols and Calcaric Arenosols that formed there. Their epipedon is close to mollic although humus is rich in carbon and poor in nitrogen. A high C:N ratio (>20) appears to demonstrate still weak nitrogen bridges in the polyphenolic molecules of humus substances. At the same time, the large portion of insoluble residue and an insignificant amount of free fulvic acids can be due to the participation of oxidized kukersite in humus formation as well as rapid humification of plant remains in seasonally arid calcareous conditions. Differences in the degree of humification and total fulvicity between Regosols and Arenosols suggest that the plant/litter origin of humus prevails. This is also confirmed by the predominance of R_2O_3-humic–fulvic complexes over compounds bound with alkaline earths.

Development of pedogenetic argillization was still insufficient, owing to which the main exchange capacity can be attributed to the colloidal complex of humus origin. Lack of exchangeable acidity and a clearly alkaline reaction are characteristic of soils with a high content of organic reagents. Accumulation of amorphous iron and increase in iron activity seem to be diagnostic of the development of cambic properties there. Accumulative phenomena in primary pedogenesis correspond exactly to the high productivity of stands and progress in the functioning of the forest–soil system.

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MULDADE ARENG PÕLEVKIVIKARJÄÄRIDE KARBONAATSEL PUISTANGUL KOLMEKÜMNE AASTA JOOKSUL

Loit REINTAM ja Elmar KAAR

Kohtla ja Viivikonna kuuel katsealal uuriti põlevkivikarjääride puistangutele rajatud metsakultuuride all 29–35 aasta jooksul kujunenud huumus-akumulatiivse profiiliga muldi. Tegemist on erakordselt intensiivse produktsiooniprotsessi (tagavara aasta keskmine suurenemine 5,7–8,5 tm ha^{-1}) väljundiga, kus oluliseks mõjuriks on 2–5 cm tüsedune *Moder*- ja/või *Mull-Moder*-tüüpi metsakõdu. Selle alla moodustunud huumushorisont on 5–30 cm tüsedune, orgaanilise süsiniku rikas (valdavalt üle 6%), kuid lämmastikuvaene – C:N >20. Huumuses on ohtralt humiinaineid, enamik huumushappeid on seotud liikuvate raudoksiididega. Fulvohapete vabade vormide osakaal on väike, mistõttu mineraalosa muundumine ja sekundaarse savi moodustumine on veel vähemärgatav. Kuigi kaevandamisel ja järgneval tasandamisel puistangusse sattunud põlevkivijäänustest osa võis hapendumise käigus humifitseeruda ning osaleda mulla huumusprofiili kujunemisel, näitab huumusainete grupiline ja fraktsiooniline koostis metsataimede jäänuste esmast kohta mullatekkeprotsessis. Nõrga savistumise foonil etendavad neelavaski kompleksis peamist osa huumuskolloidid. Neutraalse reaktsiooniga ning alustest küllastunud muldades ilmnevad esmased tunnused mittesilikaatsete rauaühendite kogunemisest kohapeal. Seega on lisaks *mollic*-tüübile lähedase huumushorisondi olemasolule kujunemas ka *cambic*-tunnused huumushorisondi allosas ja lähtekivimi piiril. Primaarses mullatekkes kujunenud karbonaatsed mullad kuuluvad FAO süsteemis *Regosol*'i ja *Arenosol*'i hulka.