Proc. Estonian Acad. Sci. Biol. Ecol., 1997, **46**, 3, 174–190

https://doi.org/10.3176/biol.ecol.1997.3.07

PEDOGENETIC CHANGES IN THE QUANTITY AND DISTRIBUTION OF TEXTURAL AND CHEMICAL SOIL CONSTITUENTS DURING THIRTY YEARS

Loit REINTAM

Institute of Soil Science and Agrochemistry, Estonian Agricultural University, Viljandi mnt., Eerika, EE-2400 Tartu, Estonia

Received 25 February 1997, accepted 3 June 1997

Abstract. A special experiment was established in 1963 and initiated in 1964 to study pedogenesis under grass-herbaceous vegetation on reddish-brown calcareous till. The results of the first two decades as well as changes in the organic pedogenetic agents and in some mobile soil properties during the third decade of pedogenesis and within the transient period of thirty years have been discussed earlier. This paper deals with the pedogenetic changes in the quantity and distribution of textural and chemical constituents during the total period of the investigations. The synchronous weathering of sandy fractions and accumulation of silty-clayey particles are characteristic of primary pedogenesis on reddish-brown calcareous till. Against the background of these phenomena and the humus-accumulative process loosening and annual upward growth of solum occurred. The mean annual growth of solum was 1 mm under the conditions of permanent full humus accumulation and 0.4–0.5 mm under partial elimination of organic agents. Mineral particles coarser than 0.01 mm indicate that soil sections of 60 cm formed on the initial till prisms of 57–61 cm. Argillization *in situ* results in the formation of cambic properties under the thin ochric epipedon and accumulation of sesquioxides, titanium, calcium, etc. by 1.5–3.5% of their content in the initial till. In spite of the annual losses of potassium up to 70 g m^{-2} no hydrolytic processes and cheluviation of pedogenetic products occurred even in the conditions of partial elimination of organic agents. A slight translocation of fine particles and their chemical constituents within the topsoil can be connected with initial weak lessivage, but the concept of a physical separation of fine-dispersed material as a result of the alternation of frozening and thawing within the epipedon without pedogenetic processes seems to be preferred. The primary progress of Calcaric Cambisol (Rendollic Eutrochrept) can be diagnosed on the basis of the data obtained.

Key words: experimental modelling, primary pedogenesis, granulometric and chemical composition, changes in soil mineral constituents.

INTRODUCTION

According to widespread concepts the nature of pedogenesis is specified by a highly complicated influence of organic matter on the mineral stratum of a weathering crust (parent rock of a soil) in a certain ecological situation. This results in the transformation of parent material into soil horizons and in the formation of a soil section representing the direct output of organic and mineral interactions in the presence and participation of solar radiation, moisture, and gases. As the horizon differentiation is a function of additions, removals, transfers, and transformation within the soil section formed and forming (Simonson, 1959) material gains and losses can be interpreted as an active process in the soil development (Arnold, 1965).

Primary soil, which functions in the top of the mineral stratum under the ground vegetation, forms rapidly, but it takes more time to become a well-developed and differentiated profile mantle (Arnold et al., 1990). Development of genetic diagnostics is a complicated prolonged temporal and spatial process (Wilding et al., 1983; Zonn, 1986, 1994, 1996). To study the modern synchronous production and pedogenetic processes in a certain situation and to study both the rate and trends of any change taking place in ecosystem characteristics, the method of experimental modelling was introduced and is increasingly often used (Simonson, 1959; Hoosbeek & Bryant, 1994). Mostly attention has been focused on quantification of pedogenetic processes over short time. In such cases increments of solum reflect seasonal changes in organic and mineral sectional properties. Besides the special experimental models that show a rapid progress of soil formation, valuable pedogenetic and ecosystem information has been received on the basis of recultivated mine territories and research into archaeological objects (Reintam, 1995).

To explain the formation of humus relationships, pedogenetic activity of herbaceous vegetation, and changes in the composition of parent material, a special experiment on reddish-brown calcareous till was founded in 1963 under natural conditions. Some changes in the balance of substances and also in the initial constituents of reddish-brown till within the primary pedogenesis during the first decade and the first two decades were published (Reintam, 1982; Reintam & Pogorelova, 1987). Changes in organic pedogenetic agents and in some mobile soil properties during the third decade of pedogenesis as well as within the transient period of thirty years were also summarized and discussed (Reintam, 1995). The objective of this paper is to deal with the pedogenetic changes in the quantity and distribution of textural and chemical constituents during the whole study period. Although the material and some methods of these studies were described earlier (Reintam, 1995), it seems to be indispensable to briefly repeat them here.

MATERIAL AND METHODS

Foundation of the experiment, layout, and variants

The experiment was founded at Eerika, Tartu County, Estonia (58º22´ N, 26º36´ E) in the autumn of 1963. *Albi-Eutric Luvisol* profile on reddish-brown calcareous till was excavated to a depth of 2 m in an area of 9 m^2. The pit formed was divided into four equal parts (2.25 m^2 each), isolated from every side by saturated felt, and filled with unchanged reddish-brown calcareous till dug up from the neighbouring cellar-pit of a lysimeter building from a depth of 1.5–3 m. The initial bulk density (1.71 $Mg\ m^{-3}$) of the till transferred was preserved by the volume.

The actual experiment was initiated in the spring of 1964 after the natural winter subsidence and the formation of the agricultural herbaceous vegetation sown. The four variants differing in their organic sources for pedogenesis were as follows at the end of the third decade:

(1) *G–G–G+* : 1964–73 – white clover and grasses without harvesting, 1974–83 – grasses and herbs without harvesting, 1984–93 – grasses and herbs weighed and returned; **all the grass–herbaceous biomass formed represented the source for pedogenesis.**

(2) *L–G–G–* : 1964–73 – hop lucerne without harvesting, 1974–83 – spontaneous grasses and herbs without harvesting, 1984–93 – vegetation weighed and eliminated; **on the background of the previous complete accumulation of organic residues, prevailed elimination during the last decade.**

(3) *B–G–BG+* : 1964–73 – summer barley without harvesting, 1974–83 – spontaneous grasses and herbs without harvesting, 1984–87 – barley weighed, grains eliminated, straw and spontaneous hop lucerne and weeds returned, 1988–93 – spontaneous hop lucerne, grasses and herbs weighed and returned; **on the background of annual vegetation, perennial herbage with the intermittent accumulation and elimination of residues.**

(4) *O–G–G+* : 1964–73 – without vegetation, 1974–83 – spontaneous herbs and grasses without harvesting, 1984–93 – vegetation weighed and returned; **on the background of a continuous absence of organic agents complete accumulation of spontaneous biomass formed to the advantage of pedogenesis.**

Sampling

The morphological description and sampling of the profiles developed were carried out to the depth of 60 cm three times (early May of 1974, 1984, 1994) by the traditional and well-known in soil science way separately for the microfabric investigations, bulk density determination (in four replications using a barrel of 50 cm^3), and laboratory techniques. The solum dug up from the profile described was returned by layers and covered with a natural piece of turf from the same place to change the situation as little as possible. The aboveground phytomass was cut 3–4 times in the vegetation period and the results were expressed in absolute dry weight.

Analyses

Analytical techniques were carried out in the laboratories of the Institute of Soil Science & Agrochemistry, Estonian Agricultural University, by Raja Kährik, a research assistant. Fine earth less than 1 mm was used. Samples for the particle size determination were treated with sodium pyrophosphate to break aggregates down. Sands were sieved and the fractions finer than 0.05 mm were determined by pipette analysis. Total chemical analysis after the alkaline fusion treatment was carried out. Iron and aluminium were ascertained by means of sulphosalicylic acid and aluminone, respectively, alkaline earths by the complexometric method with the help of trilon B, potassium and sodium by the method of flame photometry (Arinushkina, 1970). The authenticity of these techniques was verified by the method of AAS.

The group and fractional composition of humus discussed earlier (Reintam, 1995) was determined by the alternate acid–alkaline treatment after the Tyurin–Ponomareva volumetric method (Ponomareva, 1957). The obtained results were expressed in the percentage of organic carbon. The total percentage of organic carbon and nitrogen were ascertained by the Tyurin and Kjeldahl methods, respectively (Orlov, 1985). Nonsiliceous iron after Coffin, amorphous sesquioxides and silica after Tamm, and iron activity after Schwertmann were determined (Zonn, 1982). Supplies of granulometric fractions and chemical elements were calculated on the basis of particular thickness of the layers (horizons) described and the bulk density determined.

Calculation of changes in till constituents

To ascertain the quantitative origin of profile differentiation within primary pedogenesis the material balance method was used (Targulian et al., 1974; Reintam, 1985, 1990). Differences in the weight of the soil horizons formed as well as their textural and chemical constituents were compared with those in the initial reddish-brown till prior to the foundation of the experiment as follows:

$$y = M\,(BD_1 \times x_1 - Bd_0 \times x_0), \qquad (1)$$

where y difference in the weight of fractions (elements) investigated in comparison with the initial, ± kg m^{-2};

M thickness of a soil horizon formed and the initial till corresponding to the latter, dm;

BD_1 bulk density of soil;

Bd_0 bulk density of the initial material;

x_1 percentage of the fraction (chemical) examined in the soil;

x_0 percentage of the fraction (chemical) examined in the initial till.

As any change in the initial bulk density in the course of pedogenesis brings about a change in the total weight of a respective horizon, the thickness of the horizon and the amount of all constituents therein, the trends and character of transformations were explained with the help of mineral indicators (Rozanov, 1975). Fractions of sand and coarse silt (>0.01 mm) resistant to biological weathering and pedogenesis were regarded as an indicator of the initial status of the parent till. The formation of humus and organo-mineral complexes as well as of the structural aggregates characteristic of pedogenesis is always connected with the loosening of soil and upward growth of the profile formed. Vice versa, the compacting of the solum formed results in the subsidence of the soil section simultaneously with the relative accumulation of resistant indicators (Rozanov, 1975; Targulian et al., 1974; Reintam, 1985, 1990). Changes in the thickness of the initial till prism ($CTITP$ ± cm) were calculated as follows:

$$CTITP = \frac{TS \times CWI}{WIT}, \tag{2}$$

where TS the thickness of the solum studied (= 60 cm);
WIT the weight of indicators (particles >0.01 mm) in till (kg m^{-2});
CWI changes in the weight of indicators during pedogenesis (± kg m^{-2}).

Carbonates in sand and coarse silt fractions cannot be used as indicators. Their pedogenetic breakdown leads to a decrease in the weight of solum whereas residual crystalline indicators (quartz, unchanged feldspars, etc.) are available to show the character of transformation processes. Such a recalculation of the thickness of the initial till prism made it possible to take into consideration the upward growth and/or downward subsidence of stratum during pedogenesis and to find out the real changes in textural and chemical constituents:

$$SWT = \frac{WCT \times ST}{TS}, \tag{3}$$

where SWT the smoothed weight of a constituent in till with smoothed thickness;
WCT the weight of constituent in till (kg m^{-2});
TS the thickness of a horizon (solum);
ST the smoothed thickness of a respective prism of the initial till.

The smoothed thickness calculated by the sand and silt indicators was also used in the recalculation of changes in chemical constituents. This method has been successfully approbated not only by Targulian et al. (1974) and the author of this paper (Reintam, 1985), but also by numerous other authors cited in the publications above.

RESULTS AND DISCUSSION

During the 30-year period the humus-accumulative process progressed whereas the accumulation of organic carbon and nitrogen was nearly equivalent to the amount of humifiable phytocoenotic agents (Table 1; Reintam, 1995).

Table 1

Organic agents accumulated during thirty years of pedogenesis

Variant	Thickness of layer, cm	Org. C	N	C : N	H.a./F.a.	1st fr. / 2nd fr.	Degree of humification, %	Soluble, % of total
		g m^{-2}						
G–G–G+	0–5	986	104	9.5	0.5	1.9	14	56
	5–10	735	76	10.5	0.2	5.2	5	54
	10–20	404	60	6.7	0.1	0.1	6	84
	0–20	2125	240	8.8	x	x	10	62
	20–40	184	29	6.3	x	x	x	x
	40–60	124	32	3.9	x	x	x	x
	0–60	2433	301	8.1	x	x	x	x
L–G–G–	0–5	701	66	10.6	0.8	5.0	10	56
	5–10	331	31	10.7	0.3	16.0	6	49
	10–20	191	19	10.0	0.2	1.6	7	53
	0–20	1223	116	10.5	x	x	8	54
	20–40	256	51	5.0	x	x	x	x
	40–60	33	34	1.0	x	x	x	x
	0–60	1512	201	7.5	x	x	x	x
B–G–BG+	0–5	895	84	10.7	0.2	27.5	9	45
	5–10	538	48	11.2	0.3	6.6	7	54
	10–20	122	5	24.4	0.2	0.3	10	78
	0–20	1555	137	11.3	x	x	8	51
	20–40	107	0	107.0	x	x	x	x
	40–60	67	0	67.0	x	x	x	x
	0–60	1729	137	12.6	x	x	x	x
O–G–G+	0–5	925	79	11.7	0.3	51.3	8	54
	5–10	260	25	10.4	0.3	0.2	6	72
	10–20	311	20	15.6	0.1	6.4	4	42
	0–20	1496	124	12.1	x	x	7	61
	20–40	194	35	5.5	x	x	x	x
	40–60	147	66	2.2	x	x	x	x
	0–60	1837	225	8.2	x	x	x	x

---

* H.a./F.a., ratio of humic and fulvic acids; x, undetermined.

The formation of ochric epipedon reached down to 5–8 cm. The mean annual increment amounted to 1.7–3 mm in depth. The rate over 2.5 mm was characteristic of the last decade. Except the *B–G–BG+* variant, 41–50% of the organic carbon and 33–35% of the nitrogen accumulated in the very top of the epipedon. Because of the thin-rooted annual vegetation and the spontaneous seasonal occurrence of hop lucerne, 62% of the carbon and 54% of the nitrogen accumulation concentrated at a depth of 5 cm in this variant. As a result of unification in depth, 81–90% of the organic agents of pedogenesis were found in a 20 cm layer.

R_2O_3-fulvic humus, quite perfect by C : N ratio, was characteristic of the objects investigated (Table 1), although qualitative changes occurred by the formation of R_2O_3-fulvic complexes because of the transformation of Ca-fulvic–humic ones simultaneously with the accumulation of nonsiliceous ferric compounds there (Reintam, 1995). Against the background of such a biopedogenetic situation the leaching of carbonates, oxidation processes, transformation of organic residues and unstable humus substances, enrichment of humus with nitrogen, and transformation of mobile sesquioxides were described as characteristic processes of primary pedogenesis.

Organic impacts on the mineral constituents of reddish-brown till result in the progress of argillization and clay translocation within the layers influenced (Table 2). Redistribution of fractions demonstrates the accumulation of silt and clay as a result of the pedogenetic breakdown of fine sand, but also the remnant accumulation of coarse and medium sand against the background of a relative decrease in the weatherable fine one. All ratios and coefficients calculated show a tendency to a slight argillization *in situ*. Clay translocation from the thin epipedon seems to have taken place.

Changes in bulk densities and organic activities are reflected in changes in the weight characteristics of soil textural constituents (Table 3). A total decrease in the weight of fine earth by 1.5–2.7% of the initial weight of till prisms tends to be connected with the breakdown of carbonates. The enrichment of fine earth with carbonates mobilized from pebbles and/or gravel results in an increase in the initial weight of the solum by the same extent (1.9%) against the background of spontaneous progress of biomass and intensification of pedogenesis (Reintam, 1995). The prevalent weathering of sand particles and accumulation of silt ones are accompanied by an apparent slight lessivage of the thin topsoil. The balance between clay eluviation–illuviation phenomena in the very thin topsoil seems to be dependent on the destiny of organic sources of pedogenesis. Lessivage is already texturally diagnostic even after the consideration of mineral indicators (Table 4) in the conditions of prevailing elimination of the aboveground production (*L–G–G–*). Nearly the same tendency was described by Wang & Arnold (1973) in their studies of pedogenesis on multisequal parent materials, and was also discussed by Rozanov (1975) and Ruellan & Dosso (1993) in their monographs on soil morphology.

Table 2

Texture of fine earth (%) *

Variant	Depth, cm	CMS	FS	CSi	MFSiCl	Cl	$\frac{\geq 0.01\text{mm}}{<0.01\text{mm}}$	$\frac{\text{MFSiCl}}{\text{Cl}}$	CD
G–G–G+	0–8	22.7	32.7	16.6	28.0	14.2	2.6	2.0	0.9
	8–15	20.1	35.5	16.4	28.0	15.4	2.6	1.8	1.0
	15–20	21.3	36.9	14.4	27.4	15.4	2.6	1.8	1.0
	20–30	19.5	37.7	13.6	29.2	15.6	2.4	1.9	1.0
	30–40	17.6	41.5	13.6	27.3	14.8	2.7	1.8	1.0
	40–50	20.2	38.2	14.4	27.2	15.2	2.7	1.8	1.0
	50–60	20.1	39.9	12.8	27.2	15.2	2.7	1.8	1.0
L–G–G–	0–5	22.2	36.5	16.1	25.2	12.6	3.0	2.0	0.9
	5–10	17.8	40.6	14.4	27.2	14.4	2.7	1.9	1.0
	10–20	18.7	40.9	13.2	27.2	14.0	2.7	1.9	1.0
	20–30	20.7	38.7	13.3	27.3	14.0	2.7	1.9	1.0
	30–40	18.7	40.1	13.6	27.6	14.2	2.6	1.9	1.0
	40–60	19.0	40.8	13.4	26.8	14.4	2.7	1.9	1.0
B–G–BG+	0–7	26.3	33.7	12.8	27.2	12.6	2.6	2.2	1.0
	7–11	21.9	37.1	14.8	26.2	13.0	2.8	2.0	1.0
	11–20	21.9	38.7	13.0	26.4	14.4	2.8	1.8	1.1
	20–30	20.8	38.0	14.0	27.2	14.6	2.7	1.9	1.1
	30–40	21.5	38.5	12.8	27.2	15.2	2.7	1.8	1.2
	40–60	19.5	40.7	13.6	26.2	14.6	2.8	1.8	1.1
O–G–G+	0–5	22.9	37.1	15.2	24.8	14.6	3.0	1.7	1.0
	5–10	18.9	40.7	14.4	26.0	14.0	2.8	1.9	1.0
	10–20	19.4	39.0	14.4	27.2	15.2	2.7	1.8	1.1
	20–30	18.8	41.6	13.2	26.4	14.0	2.8	1.9	1.0
	30–40	19.7	41.3	14.0	26.2	14.4	2.8	1.8	1.0
	40–60	19.1	40.5	13.2	27.2	14.6	2.7	1.9	1.0
Initial till		16.6	45.5	12.6	26.3	14.1	2.8	1.9	–

---

* CMS, coarse and medium sand (1–0.25 mm); FS, fine sand (0.25–0.05 mm); CSi, coarse silt (0.05–0.01 mm); MFSiCl, medium and fine silt and clay (<0.01 mm); Cl, clay (<0.001 mm); CD, coefficient of differentiation by Siuta (1966).

Accounting the layeral status of mineral indicators the soil section of 60 cm formed during 30 years is a real result of the pedogenetic interactions on the initial till prism, which is somewhat thinner (Table 4). Loosening and upward growth of the soil sections formed are characteristic of all variants: average annual upgrowth of nearly 1 mm for the *G–G–G+* and *O–G–G+* variants

Table 3

Changes in the weight of granulometric fractions compared with the initial reddish-brown till (±kg m^{-2})

Variant	Depth, cm	Weight of prisms		Fractions				
		Initial till	Soil	Sand	Coarse silt	Medium & fine silt + clay	Total fine earth	Clay
G–G–G+	0–8	136.8	113.6	−20.7	+1.7	−4.2	−23.2	−3.1
	8–15	119.7	115.7	−8.9	+4.0	+0.9	−4.0	+0.9
	15–20	85.5	87.0	−1.5	+1.7	+1.3	+1.5	+1.3
	20–30	171.0	169.0	−7.8	+1.5	+4.3	−2.0	+2.3
	30–40	171.0	171.0	−3.4	+1.7	+1.7	0.0	+1.2
	40–60	342.0	342.0	−6.5	+3.5	+3.0	0.0	+3.8
	Total	1026.0	998.3	−48.8	+14.1	+7.0	−27.7	+6.4
L–G–G–	0–5	85.5	69.0	−11.8	+0.4	−5.1	−16.5	−3.3
	5–10	85.5	79.5	−5.8	+0.7	−0.9	−6.0	−0.7
	10–20	171.0	177.0	+1.0	+1.9	+3.1	+6.0	+0.7
	20–30	171.0	172.0	−2.3	+1.3	+2.0	+1.0	0.0
	30–40	171.0	170.0	−4.5	+1.6	+1.9	−1.0	0.0
	40–60	342.0	340.0	−5.7	+2.6	+1.1	−2.0	+0.8
	Total	1026.0	1007.5	−29.1	+8.5	+2.1	−18.5	−2.5
B–G–BG+	0–7	119.7	108.5	−8.0	−1.2	−2.0	−11.2	−4.6
	7–11	68.4	65.6	−3.1	+1.1	−0.8	−2.8	−1.1
	11–20	153.9	153.9	−0.8	+0.7	+0.1	0.0	+0.5
	20–30	171.0	168.0	−5.7	+2.0	+0.7	−3.0	+0.4
	30–40	171.0	175.0	+0.5	+0.9	+2.6	+4.0	+2.5
	40–60	342.0	340.0	−4.3	+3.2	−0.9	−2.0	+1.4
	Total	1026.0	1011.0	−21.4	+6.7	−0.3	−15.0	−0.9
O–G–G+	0–5	85.0	80.0	−4.3	+1.5	−2.7	−5.5	−0.3
	5–10	85.0	84.0	−2.1	+1.3	−0.7	−1.5	−0.3
	10–20	171.0	180.0	+0.6	+4.4	+4.0	+9.0	+3.3
	20–30	171.0	179.0	+3.6	+2.1	+2.3	+8.0	+1.0
	30–40	171.0	171.0	−1.3	+2.0	−0.7	0.0	+0.1
	40–60	342.0	352.0	+0.8	+3.5	+5.7	+10.0	+3.2
	Total	1026.0	1046.0	−2.7	+14.8	+7.9	+20.0	+7.0

Table 4

Changes in the weight of granulometric fractions compared with the smoothed thickness of the initial reddish-brown till (±kg m^{-2})

Variant	Depth of till, cm	Weight of prisms		Fractions				
		Soil	Smoothed till	Sand	Coarse silt	Medium & fine silt + clay	Total fine earth	Clay
G–G–G+	6.5	113.6	111.1	–5.0	+4.9	+2.6	+2.5	+0.5
	6.6	115.7	112.8	–4.7	+4.9	+2.7	+2.9	+1.9
	5.0	87.0	85.5	–1.5	+1.7	+1.3	+1.5	+1.3
	9.5	169.0	162.5	–2.6	+2.6	+6.5	+6.5	+3.5
	9.9	171.0	169.3	–2.3	+1.9	+2.1	+1.7	+1.4
	19.7	342.0	336.9	–3.4	+4.1	+4.4	+5.1	+4.5
	57.2	998.3	978.1	–19.5	+20.1	+19.6	+20.2	+13.1
L–G–G–	4.1	69.0	70.1	–2.4	+2.3	–1.0	–1.1	–1.1
	4.6	79.5	78.6	–1.6	+1.6	+0.9	+0.9	+0.3
	10.2	177.0	174.4	–1.1	+1.5	+2.2	+2.6	+0.2
	9.9	172.0	169.3	–1.2	+1.5	+2.4	+2.7	+0.2
	9.8	170.0	167.6	–2.4	+2.0	+2.8	+2.4	+0.5
	19.8	340.0	338.6	–3.6	+3.0	+2.0	+1.4	+1.3
	58.4	1007.5	998.6	–12.3	+11.9	+9.3	+8.9	+1.4
B–G–BG+	6.3	108.5	107.7	–0.7	+0.3	+1.2	+0.8	–2.9
	3.8	65.6	65.0	–1.0	+1.5	+0.1	+0.6	–0.6
	9.0	153.9	153.9	–0.8	+0.7	+0.1	0.0	+0.5
	9.7	168.0	165.9	–2.6	+2.7	+2.0	+2.1	+1.1
	10.1	175.0	172.7	–0.6	+0.7	+2.2	+2.3	+2.3
	19.9	340.0	340.3	–3.2	+3.4	–0.5	–0.3	+1.6
	58.8	1011.0	1005.5	–8.9	+9.3	+5.1	+5.5	+2.0
O–G–G+	4.8	80.0	82.1	–2.2	+1.9	–1.8	–2.1	+0.2
	4.9	84.0	83.8	–1.1	+1.5	–0.2	+0.2	0.0
	10.4	180.0	177.8	–3.6	+3.6	+2.2	+2.2	+2.3
	10.4	179.0	177.8	–0.6	+1.3	+0.5	+1.2	+0.1
	10.0	171.0	171.0	–1.3	+2.0	–0.7	0.0	0.0
	20.4	352.0	348.9	–3.4	+2.6	+3.9	+3.1	+2.2
	60.9	1046.0	1041.4	–12.2	+12.9	+3.9	+4.6	+4.8

(complete accumulation of biomass) and 0.4–0.5 mm for the *L–G–G–* and *B–G–BG+* variants (prevalent elimination of organic agents) was recorded. Both the elimination of the aboveground production and a decade-long alternation of annual and perennial vegetation seem to favour a slight lessivage of the thin epipedon. Argillization *in situ* leads to the development of visible and analytically determinable cambic properties. This process is more evident in the conditions of permanent accumulation of all organic residues (*G–G–G+*). The absolute increase in the source of fine earth and clay formed 2.1 and 1.3%, respectively.

Though a tendency to textural differentiation within the epipedon was found in the variants of prevalent and/or decade-long elimination of organic residues (Tables 2–4), morphological signs of eluviation, clayskins, and argillic properties were still absent there. Altogether, an increase in the absolute amounts of fine earth and clay by 0.4–0.9 and 0.1–0.4%, respectively, has taken place. Moreover, the epipedon is seasonally subjected to frost action and the sorting of particles within the thin banded topsoil could also be attributed to it (Mermut & St. Arnaud, 1981). During the thaw period finer particles can exist as a fluid suspension, resulting in a physical separation of particles within the band.

Pedogenetic impacts on the percentage of chemical constituents are negligible, but highly variable (Table 5). Except basic products of the weathering of alumosilicates, a tendency to accumulative phenomena could be observed simultaneously with the breakdown of sand and accumulation of silt and clay (Tables 2–4). The epipedon enriched with biogenic elements (Table 1) was slightly impoverished not only by clay, but also by the chemical constituents of clay (Table 6). At that the total soil sections of all variants are accumulative and there the gains consist of about 1% (up to 2%) of the initial till status. The losses of secondary quartz, magnesium, and potassium of alumosilicates and simultaneous accumulation of sesquioxides, titanium, and calcium tend to demonstrate the progress of slight ferrallitization (Zonn, 1986), formation of chlorites, and fixation of calcium in the structure of secondary alumosilicates (Reintam, 1971). According to Aniku & Singer (1990) the progressive transformation of ferrihydrates into christalline Fe-oxides develop already in a short period of time (Reintam, 1995). The loosening and upward growth of the solum, characteristic of pedogenesis on calcareous reddish-brown till (Reintam, 1985), through the textural transformation (Table 4) led to the total accumulation of chemical constituents in the solum of 60 cm by 3.5% of the initial in the conditions of permanent (complete) accumulation of organic agents for pedogenesis (*G–G–G+*), and by 1.4–2.0% of the initial in the other cases. At that, against the background of a quite similar annual rate of pedogenetic accumulation of aluminium and calcium (130–160 and 120–190 g m^{-2}, respectively, in the section of 60 cm), permanent restoration of organic matter, which sets the soil processes into motion, has enabled the fixation of iron, whose annual rate is two- to threefold as intensive as in the conditions of residues elimination – 89–90 and 30–40 g m^{-2}, respectively (Table 7). Highly seasonal reductomorphic phenomena in the thin epipedon could have affected the decrease in iron relationship there (Macedo & Bryant, 1989) whereas freeze–thaw interactions affecting fine particles are not excluded (Mermut & St. Arnaud, 1981). Because of the relatively rapid weathering of orthoclase (to a lesser extent of albite, anorthite, and other plagioclases) the annual losses of potassium from the section of 60 cm amount to 30–40 $g\ m^{-2}$ and only the intensification of plant–soil interactions can ensure its layeral pedogenetic gain.

Table 5

Chemical composition (%) of the ignited noncalcareous soil

Variant	Depth, cm	Si	Fe	Al	Ti	P	Ca	Mg	K	Na	Mn
G–G–G+	0–8	37.96	1.75	4.40	0.35	0.08	1.58	1.36	2.75	0.60	0.08
	8–15	38.93	1.88	4.42	0.34	0.07	2.13	1.88	2.80	0.53	0.08
	15–20	38.22	1.84	4.52	0.32	0.06	1.96	1.89	2.56	0.54	0.08
	20–30	38.39	1.94	4.96	0.36	0.07	1.80	1.88	2.75	0.57	0.09
	30–40	38.96	2.03	4.43	0.32	0.06	1.29	1.82	2.56	0.57	0.07
	40–50	38.46	1.94	4.46	0.29	0.06	1.47	1.19	2.73	0.47	0.09
	50–60	37.83	2.38	4.73	0.36	0.06	1.24	1.20	2.65	0.45	0.06
L–G–G–	0–5	37.85	2.05	4.42	0.34	0.10	1.83	2.02	2.55	0.57	0.07
	5–10	37.75	1.71	4.43	0.26	0.08	2.00	2.01	2.47	0.67	0.06
	10–20	37.65	1.71	4.42	0.29	0.10	1.26	0.88	2.49	0.73	0.08
	20–30	37.42	1.79	4.48	0.24	0.07	1.38	0.72	2.53	0.57	0.08
	30–40	37.76	1.78	4.47	0.27	0.08	1.33	1.28	2.51	0.63	0.08
	40–60	37.78	2.06	4.74	0.28	0.06	1.61	1.24	2.60	0.56	0.08
B–G–BG+	0–7	37.99	1.64	4.41	0.24	0.08	1.94	1.41	2.07	0.63	0.05
	7–11	38.36	1.76	4.47	0.32	0.07	1.74	1.47	2.10	0.57	0.05
	11–20	37.89	1.96	4.43	0.32	0.10	1.02	1.40	2.57	0.53	0.07
	20–30	38.66	1.89	4.75	0.36	0.09	1.30	1.35	2.56	0.40	0.06
	30–40	38.63	1.73	4.43	0.25	0.12	1.86	1.30	2.50	0.42	0.06
	40–60	38.06	1.93	4.94	0.25	0.11	1.87	1.38	2.46	0.48	0.06
O–G–G+	0–5	38.55	1.88	4.47	0.30	0.11	2.02	1.40	2.36	0.46	0.05
	5–10	39.58	2.20	5.09	0.30	0.14	2.02	1.40	2.81	0.80	0.05
	10–20	37.70	1.77	4.33	0.35	0.09	1.24	1.04	2.68	0.68	0.05
	20–30	37.72	1.99	4.44	0.29	0.10	1.42	1.13	2.58	0.70	0.05
	30–40	38.05	2.08	4.48	0.31	0.12	1.41	1.41	2.57	0.69	0.05
	40–50	37.76	2.06	4.82	0.33	0.08	1.22	0.90	2.35	0.75	0.07
Initial till		37.73	1.77	4.21	0.25	0.06	1.06	1.15	2.68	0.54	0.06

Table 6

Changes in the weight of chemical constituents compared with the initial reddish-brown till (±kg m^{-2}) *

Variant	Depth, cm	Si	Fe	Al	Ti	P	Ca	Mg	K	Na	Mn
G–G–G+	0–8	–8.5	–0.4	–0.8	+0.1	+0.02	+0.3	–0.1	–0.6	0.0	+0.02
	8–15	–0.2	+0.1	+0.1	+0.1	+0.01	+1.2	+0.8	0.0	0.0	+0.02
	15–20	+1.0	+0.1	+0.3	+0.1	0.00	+0.8	+0.6	–0.1	0.0	+0.02
	20–30	+1.2	+0.2	+1.2	+0.2	+0.01	+1.2	+1.2	0.0	+0.1	+0.04
	30–40	+2.1	+0.5	+0.4	0.0	0.00	+0.4	+1.2	–0.2	+0.1	+0.02
	40–60	+1.4	+1.3	+1.3	+0.2	0.00	+1.0	+0.2	+0.1	–0.3	+0.04
	Total	–3.0	+1.8	+2.5	+0.7	+0.04	+4.9	+3.9	–0.8	–0.1	+0.16
L–G–G–	0–5	–6.2	–0.1	–0.5	0.0	+0.02	+0.4	+0.4	–0.5	0.0	0.00
	5–10	–2.3	–0.1	–0.1	0.0	+0.01	+0.6	+0.6	–0.3	0.0	0.00
	10–20	+2.1	0.0	+0.6	0.0	+0.08	+0.4	–0.4	–0.2	+0.4	+0.04
	20–30	–0.1	0.0	+0.5	0.0	+0.02	+0.6	–0.8	–0.2	+0.1	+0.04
	30–40	–0.3	0.0	+0.4	+0.1	+0.04	+0.5	+0.3	–0.3	+0.2	+0.04
	40–60	–0.5	+0.9	+1.7	+0.1	–0.02	+1.9	+0.3	–0.3	0.0	+0.05
	Total	–7.3	+0.7	+2.6	+0.2	+0.15	+4.4	+0.4	–1.8	+0.7	+0.17
B–G–BG+	0–7	–4.0	–0.3	–0.2	+0.1	+0.02	+0.8	+0.1	–0.9	+0.1	–0.02
	7–11	–0.6	0.0	0.0	0.0	+0.01	+0.4	+0.2	–0.4	0.0	–0.01
	11–20	+0.2	+0.3	+0.3	+0.1	+0.06	–0.1	+0.3	–0.1	0.0	+0.02
	20–30	+0.5	+0.1	+0.8	+0.2	+0.05	+0.4	+0.7	–0.3	–0.2	0.00
	30–40	+3.1	0.0	+0.6	0.0	+0.11	+1.4	+0.4	–0.2	–0.2	0.00
	40–60	+0.4	+0.5	+2.4	0.0	+0.15	+2.7	+1.1	–0.8	–0.3	–0.02
	Total	–0.4	+0.6	+3.9	+0.4	+0.40	+5.6	+2.8	–2.7	–0.6	–0.03
O–G–G+	0–5	–1.5	0.0	0.0	0.0	+0.04	+0.7	+0.1	–0.4	0.0	–0.01
	5–10	+0.9	+0.3	+0.7	0.0	+0.07	+0.7	+0.2	+0.1	+0.2	–0.01
	10–20	+3.4	+0.2	+0.6	+0.2	+0.06	+0.4	–0.1	+0.2	+0.3	–0.01
	20–30	+3.0	+0.5	+0.8	0.0	+0.08	+0.7	0.0	0.0	+0.4	–0.01
	30–40	+0.6	+0.6	+0.5	+0.1	+0.11	+0.6	+0.5	–0.2	+0.3	–0.01
	40–60	+3.9	+1.1	+2.6	+0.3	+0.06	+0.7	–0.7	–0.8	+0.7	+0.03
	Total	+10.3	+2.7	+5.2	+0.6	+0.42	+3.8	0.0	–1.1	+1.9	–0.02

---

* See weight of prisms in Table 3.

Table 7

Changes in the weight of chemical constituents compared with the smoothed thickness of the initial reddish-brown till (± kg m^{-2}) *

Variant	Depth, cm	Si	Fe	Al	Ti	P	Ca	Mg	K	Na	Mn
G–G–G+	0–8	+1.3	0.0	+0.3	+0.1	+0.02	+0.6	+0.2	+0.1	+0.1	+0.02
	8–15	+2.4	+0.2	+0.3	+0.1	+0.01	+1.3	+0.9	+0.2	0.0	+0.02
	15–20	+1.0	+0.1	+0.3	+0.1	0.00	+0.8	+0.6	–0.1	0.0	+0.02
	20–30	+4.4	+0.4	+1.6	+0.2	+0.02	+1.3	+1.3	+0.2	+0.1	+0.05
	30–40	+2.7	+0.5	+0.5	+0.1	0.00	+0.4	+1.2	–0.1	+0.1	+0.02
	40–60	+3.3	+1.5	+1.5	+0.3	+0.02	+1.0	+0.2	+0.2	–0.2	+0.06
	Total	+15.1	+2.7	+4.5	+0.9	+0.07	+5.4	+4.4	+0.5	+0.1	+0.19
L–G–G–	0–5	–0.3	+0.2	+0.1	0.0	+0.03	+0.6	+0.6	–0.1	0.0	+0.0
	5–10	+0.3	0.0	+0.2	0.0	+0.01	+0.8	+0.7	–0.1	+0.1	0.00
	10–20	+0.8	–0.1	+0.5	0.0	+0.07	+0.3	–0.4	–0.3	+0.3	+0.03
	20–30	+0.5	+0.1	+0.6	0.0	+0.02	+0.6	–0.8	–0.1	+0.1	+0.04
	30–40	+1.0	0.0	+0.5	+0.1	+0.04	+0.5	+0.3	–0.2	+0.2	+0.04
	40–60	+0.7	+1.0	+1.9	+0.2	0.00	+1.9	+0.3	–0.3	+0.1	+0.07
	Total	+3.0	+1.2	+3.8	+0.3	+0.17	+4.7	+0.7	–1.1	+0.8	+0.19
B–G–BG+	0–7	+0.6	–0.1	+0.3	+0.1	+0.03	+0.9	+0.3	–0.6	+0.1	–0.01
	7–11	+0.7	0.0	+0.2	0.0	+0.01	+0.4	+0.2	–0.4	0.0	–0.01
	11–20	+0.2	+0.3	+0.3	+0.1	+0.05	0.0	+0.3	–0.1	0.0	+0.01
	20–30	+2.4	+0.2	+1.0	+0.2	+0.05	+0.4	+0.8	–0.1	–0.2	0.00
	30–40	+2.4	0.0	+0.5	0.0	+0.11	+1.4	+0.3	–0.2	–0.2	0.00
	40–60	+1.0	+0.6	+2.5	+0.1	+0.17	+2.7	+1.1	–0.7	–0.2	0.00
	Total	+7.3	+1.0	+4.8	+0.5	+0.42	+5.8	+3.0	–2.1	–0.5	–0.01
O–G–G+	0–5	–0.2	+0.1	+0.1	0.0	+0.04	+0.8	+0.1	–0.3	0.0	–0.01
	5–10	+1.6	+0.3	+0.8	0.0	+0.07	+0.8	+0.2	+0.1	+0.2	–0.01
	10–20	+0.8	+0.1	+0.3	+0.1	+0.05	+0.3	–0.2	0.0	+0.3	–0.02
	20–30	+0.4	+0.4	+0.5	+0.1	+0.07	+0.6	–0.1	–0.2	+0.3	–0.01
	30–40	+0.6	+0.6	+0.5	+0.1	+0.11	+0.6	+0.5	–0.2	+0.3	–0.01
	40–60	+1.3	+1.0	+2.3	+0.3	+0.07	+0.6	–0.7	–0.9	+0.7	+0.04
	Total	+4.5	+2.5	+4.5	+0.6	+0.41	+3.7	–0.2	–1.5	+1.8	–0.02

---

* See smoothed thickness and weight of prisms in Table 4.

CONCLUSIONS

Synchronous weathering of sandy particles and the formation and accumulation of silty and clayey ones were characteristic of primary pedogenesis on the reddish-brown calcareous till during thirty years. These phenomena, accompanied by the humification of organic residues and progress of the humus-accumulative process, led to a decrease in the bulk density, an increase in the total porosity, loosening, and upward growth of the solum formed. The use of sand and coarse silt fractions greater than 0.01 mm as indicators resistant against weathering and pedogenesis shows the mean annual growth of solum to be up to 1 mm in the case of permanent full humus accumulation and 0.4–0.5 mm in the case of partial elimination of organic agents. This means that the soil sections of 60 cm studied really formed on the initial till prisms of 57–61 cm.

During three decades of primary pedogenesis argillization *in situ*, accumulation of fine silt and clay, and formation of cambic properties below the thin ochric epipedon occurred. In the process a pedogenetic accumulation of most chemical constituents, except potassium and some sodium, magnesium, and calcium of carbonates, took place. The annual rates of aluminium, calcium, and iron accumulation in the section of 60 cm amounted to 130–160, 120–190, and 30–90 g m^{-2}, respectively, being as high as 430 g m^{-2} in the case of clay under the impact of especially intensive organic–mineral interactions. In spite of the annual losses of potassium of up to 70 g m^{-2} these data demonstrate complete absence of hydrolytic processes and cheluviation of pedogenetic products on a reddish-brown calcareous till.

Nevertheless, a slight translocation of fine-dispersed particles and their chemical constituents could be found in the topsoil within about 20 cm. Apparent lessivage (a decrease in clay and some chemicals) tends to be significant in the thin epipedon close to the very surface. Although morphological features of clay eluviation, developed clayskins, and argillic properties are lacking, slight pedogenetic lessivage may have already begun. As the epipedon impoverished by some clay and its constituents is seasonally subjected to weak reductomorphic processes and frost action, the thin banded topsoil can be attributed to the alternate influences of freezing–thawing processes on the topsoil. That is why such particle distribution could be qualified as physical separation without the participation of pedogenetic processes. The primary progress of Calcaric Cambisol (Rendollic Eutrochrept) can be diagnosed on the basis of the data obtained.

ACKNOWLEDGEMENTS

I would like to thank Mrs. Raja Kährik, research assistant, who carried out all the laboratory techniques. Special thanks are due to Ass. Prof. Enna Sau for the revision of the English manuscript. The completion of this study was supported by the Estonian Science Foundation grant No. 2669.

REFERENCES

Aniku, J. R. F. & Singer, M. J. 1990. Pedogenetic iron oxide trends in a marine terrace chronosequence. *Soil Sci. Soc. Am. J.*, **54**, 1, 147–152.

Arinushkina, E. V. 1970. *Handbook for Soil Chemical Analyses* (in Russian). Moscow University Press.

Arnold, R. W. 1965. Multiple working hypothesis in soil genesis. *Soil Sci. Soc. Am. Proc.*, **29**, 717–724.

Arnold, R. W., Szabolcs, I. & Targulian, V. O. (eds.). 1990. *Global Soil Change. Report on an IIASA–ISSS–UNEP Task Force on the Role of Soil in Global Change.* IIASA, Laxenburg, Austria.

Hoosbeek, M. R. & Bryant, R. B. 1994. Pedodynamics: An approach to study and quantify soil forming process. In *Trans. of 15th World Congr. of Soil Science.* Vol. **6a**: *Comm. V: Symposia*, 164–178.

Macedo, J. & Bryant, R. B. 1989. Preferential microbial reduction of hematite over goethite in a Brazilian Oxisol. *Soil Sci. Soc. Am. J.*, **53**, 4, 1114–1118.

Mermut, A. R. & St. Arnaud, R. J. 1981. Microband fabric in seasonally frozen soils. *Soil Sci. Soc. Am. J.*, **45**, 3, 578–586.

Orlov, D. S. 1985. *Soil Chemistry* (in Russian). Moscow University Press.

Ponomareva, V. V. 1957. To the method for the study of soil humus after I. V. Tyurin's scheme. *Russian Soil Science* (*Pochvovedenie*), 8, 66–71.

Reintam, L. 1971. Chemical composition of brown and brown pseudopodzolic soils. In *Estonian Contribution to the International Biological Programme, II* (Frey, T. et al., eds.). Tartu, 47–88.

Reintam, L. 1982. Changes in the balance of substances within the pedogenesis under the herbaceous vegetation. In *Trans. of Estonian Agricultural Academy, 143. Soil Properties and Biological Productivity.* Tartu, 3–18.

Reintam, L. 1985. Genetic characteristics of soils on red-brown moraine compared by the substance balance method. *Soviet Soil Science*, **17**, 5, 13–22.

Reintam, L. 1990. Material-regime differentiation of soil profile in diagnostics and classification. In *Soil Classification* (Rozanov, B. G., ed.). UNEP, ISSS, Moscow, 12–19.

Reintam, L. 1995. Temporal and spatial changes in organic agents in the progress of primary pedogenesis during thirty years. *Proc. Estonian Acad. Sci. Ecol.*, **5**, 3/4, 61–76.

Reintam, L. J. & Pogorelova, T. A. 1987. Initial soil formation on red-brown calcareous moraine under herbaceous vegetation. *Soviet Soil Science*, **19**, 2, 1–13.

Rozanov, B. G. 1975. *Genetic Morphology of Soils* (in Russian). Moscow University Press.

Ruellan, A. & Dosso, M. 1993. *Regards sur le sol.* Foucher, Paris.

Simonson, R. W. 1959. Outline of a generalized theory of soil genesis. *Soil Sci. Soc. Am. Proc.*, **23**, 152–156.

Siuta, J. 1966. The relationship between the differentiation of mechanical composition, type and agricultural properties of soil. Part I. Soil type and texture. In *Pamietnik Pulawski.* PRACE IUNG, 22, 106–115.

Targulian, V. O., Sokolova, T. A., Birina, A. G., Kulikov, A. V. & Tchelicheva, L. K. 1974. *Organization, Composition and Genesis of Soddy Pale-Podzolic Soil on Mantle Loam. Analytical Study* (Russian version of a report to the X International Congress of Soil Science). Moscow.

Wang Chang & Arnold, R. W. 1973. Quantifying pedogenesis for soils with discontinuities. *Soil Sci. Soc. Am. Proc.*, **37**, 1, 271–278.

Wilding, L. P., Smeck, N. E. & Hall, G. F. (eds.). 1983. *Pedogenesis and Soil Taxonomy. 1. Concepts and Interactions.* Elsevier, Amsterdam.

Zonn, S. V. 1982. *Iron in Soils* (in Russian). Nauka, Moscow.

Zonn, S. V. 1986. *Tropical and Subtropical Soil Science*. Mir Publishers, Moscow.

Zonn, S. V. 1994. Development of soil genetic diagnostics at the basis of elementary pedogenetic processes concept. *Russian Soil Science* (*Pochvovedenie*), 4, 12–20.

Zonn, S. V. 1996. An experience of elaborating a soil genetic taxonomic system based on elementary pedogenetic processes. *Russian Soil Science* (*Pochvovedenie*), 1, 5–15.

GRANULOMEETRILISTE JA KEEMILISTE KOOSTEKOMPONENTIDE HULGA JA JAOTUMUSE MUUTUMINE MULLATEKKEPROTSESSIS KOLMEKÜMNE AASTA JOOKSUL

Loit REINTAM

1963. aastal ettevalmistatud ja 1964. aastal käivitunud katsega mullatekke kohta punakaspruunil karbonaatsel moreenil rohttaimede all selgitati kolme aastakümne jooksul toimunud muutusi mulla granulomeetriliste ja keemiliste koostekomponentide hulgas ja jaotumuses võrdluses punakaspruuni moreeni algnäitajatega. Liivafraktsiooni murenemise, sellest johtuva tolmu- ja liivaosakeste kohapeal kogunemise ning huumusakumulatiivse protsessi tagajärjel on moodustunud mullakiht kobestunud ja seetõttu kasvanud aastas ülespoole keskmiselt 1 mm orgaaniliste jäänuste täieliku akumulatsiooni ning 0,4–0,5 mm võrra nende osalise eemaldamise tingimusis. Kasutades liiva ja jämeda tolmu osakesi (üle 0,01 mm) mullatekkele vastupidavuse indikaatorina ilmnes, et 60 cm tüsedune mullakiht oli moodustunud 57–61 cm tüsedusega algmoreenil. Noore mulla rikastumine savistumisel *in situ* peente osakeste ning nendega seotud Fe, Al, Ti, Ca ja teiste elementidega moodustas 1,5–3,5% moreeni algseisust. Vaatamata K keskmisele aastakaole kuni 70 g m^{-2}, pole vähimaidki tunnuseid hüdrolüütilistest protsessidest ning neist tulenevast leetumisest isegi orgaanilise aine osalise eemaldamise foonil. Nõrk tendents õhukese huumushorisondi (epipedoni) savist ja selle koostekomponentidest vaesumiseks võib olla algava lessiveerumise tunnus, kuid välistatud pole hoopis peente osakeste füüsikaline ümberpaigutumine vahelduva külmumise ja sulamise tõttu. Leitud tunnused ja muutused mullatekkeprotsessis näitavad (leostunud) pruunmulla (Calcaric Cambisol – FAO/ISRIC; Rendollic Eutrochrept – USDA) moodustumist.