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Soil formation on reddish-brown calcareous till under herbaceous vegetation during forty years

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Abstract. A special experiment was established in 1963 and initiated in 1964 at Eerika, Tartu County, Estonia (58°22′ N, 26°36′ E) to study pedogenesis and its continuous development under grass-herbaceous vegetation on reddish-brown calcareous till which was practically free from organic carbon (0.6 g kg^{-1}) and nitrogen (0.2 g kg^{-1}). The results of the study of three earlier decades have been discussed earlier. This paper deals with the processes of synchronous production and soil formation as well as with pedogenetic activity during the fourth decade of the experiment and during the total period of 40 years. An intensive humus-accumulative process, wavy and cyclic in intensity, has continued, accompanied by the breakdown of skeletal carbonates, partial leaching of products, formation and accumulation of amorphous and crystalline nonsiliceous products of weathering, progress of argillization in situ, and slight lessivage of fine silt and clay within the thin top of enriched humus solum. Net accumulation of organic carbon and nitrogen was obtained by nearly equivalent amounts of humifiable issues of the production process. As these are temporally dynamic, the temporal periodicity of mineralization and humification relationships is also characteristic of synchronous pedogenesis. The low C : N ratio indicates an excellent quality of the humus formed since the beginning of primary soil formation. Against the background of the decadewise dynamic fulvicity of the humus and evident decrease in its total solubility, the transformation of Ca-humates into humins and the formation of R_2O_3-humic-fulvic complexes at the expense of RO-humic-fulvic complexes already during the third decade were ascertained. Intensification of the bonds of the humic-fulvic complexes with inactive sesquioxides and clay minerals and decrease in the amount of fulvic acids in the interlayeral structure of clay progressed during the fourth decade. Due to the weathering of sand fractions, an accumulation of silty-clayey particles, accompanied by an increase in the cation exchange capacity and in the specific surface area, progressed in the formed soils. The progress of Calcaric Cambisol (Rendollic Eutrochrept) can be diagnosed on the basis of data obtained during 40 years.

Key words: experimental modelling, primary production, primary pedogenesis, humus-accumulative process, humus quality, soil properties.

INTRODUCTION

Soil formation has been interpreted as a permanent and sophisticated complex of interactions between organic and mineral substances, solar radiation, moisture and gases, living beings and the inanimate environment in space and time since V. V. Dokuchaev up to modern schools of genetic and ecological soil science. Organic matter of plant, microbial, and faunal origin is the driving force, and the mineral parent stratum is the material and energetic source of the process. As differentiation of the horizons is a function of additions, removals, transfers, and transformations within formed and forming soil profiles (Simonson 1959), material gains and losses can be interpreted as an active process in soil development (Arnold 1965).

Any particular soil type, as well as the soil mantle of any territory, is subjected to the regularity of the continuum representing a reflector of the interdependences and interactions within an ecosystem (Arnold et al. 1990). To study contemporary synchronous production and pedogenetic processes in a particular ecological situation and to find out both the extent and trends of the changes taking place in ecosystem characteristics, the method of experimental modelling was introduced, research into archaeological objects was carried out, and the experiences gained from the investigation and recultivation of open-cast mined spoils (mixed detritus) was used. These materials were reviewed and referred to already in our earlier papers devoted to initial pedogenesis during 10, 20, and 30 years (Reintam 1982, 1995, 1997, 1998; Reintam & Pogorelova 1986, 1987). The results of similar studies on initially humus-free substrates were published later (Graham et al. 1995; Tice et al. 1996; Reuter 1998; Beschow et al. 2000; Reintam 2003, 2004). Focus has always been placed on the formation of humus

as the driving force for pedogenesis and its status in the soil, on the progress of production phenomena in the ecosystem, and on organic impacts on changes in textural, chemical, and other characteristics of the material that transformed into soil.

To explain the formation of humus relationships and the pedogenetic activity of the herbaceous vegetation on reddish-brown calcareous till, a special experiment was established in 1963 under natural climatic conditions. The objectives of this paper were to deal with changes in the humus status, main properties and morphology of the soil both during the fourth decade (1994–2003) and during 40 years of the experiment.

MATERIAL AND METHODS

Foundation, layout, and variants of the experiment

The experiment was established at Eerika, Tartu County, Estonia (58°22′ N, 26°36′ E) in autumn 1963. The Albic Luvisol profile on reddish-brown calcareous till was excavated to a depth of 2 m in an area of 9 m^2. The formed pit was divided into four equal sections (2.25 m^2 each), isolated from every side with saturated felt, and filled with unchanged reddish-brown calcareous till (68 g kg^{-1} of $CaCO_3$) dug from the neighbouring cellar-pit of a lysimeter building at a depth of 1.5–3 m. The initial bulk density (1.71 ± 0.02 Mg m^{-3}) of the transferred till was preserved according to volume. The till was practically free from organic carbon (0.6 g kg^{-1}) and nitrogen (0.2 g kg^{-1}), the content of clay, silt, and sand was 141, 248, and 611 g kg^{-1}, respectively. A thorough initial characterization of the till was published in 1982 (Reintam 1982).

The actual experiment was initiated in the spring of 1964 after natural winter subsidence and formation of the sown agricultural herbaceous vegetation. Initially, the experiment included four variants: (1) white clover and grasses pasture sward, (2) hop lucerne (*Medicago lupulina*), (3) summer barley, and (4) without vegetation. During the first decade the crop was not harvested and total above- and underground biomass entered natural cycling for the advantage of soil formation. Only summer barley was newly sown every spring. The fourth variant was kept free from vegetation. Because of objective reasons, it was impossible to continue the experiment according to this scheme during the second decade, and all variants were spontaneously covered with grass-herbaceous vegetation, both white clover and hop lucerne being ousted from the sward. Biomass was completely utilized as an energetic-substantial source for pedogenesis in situ. In 1984 the biomass left standing from the previous year was cut and weighed. The data obtained, together with the material published earlier, were used for the quantitative evaluation of the approximate production and pedogenetic activity of 20 years (Reintam & Pogorelova 1986, 1987).

The results of pedogenesis during the first (1964–73) and second (1974–83) decades of the experiment were analysed, presented, and discussed in the MSc papers of Virve Olvi (1976) and Tatyana Pogorelova (1986), respectively. Further changes in the balance of substances and in the initial constituents of reddish-brown till in the course of primary pedogenesis during the first and the first two decades were published (Reintam 1982; Reintam & Pogorelova 1986, 1987) and summarized in Pogorelova's PhD dissertation defended at Kharkov Agrarian University, Ukraine, in 1989 (Pogorelova 1989).

As during the second decade a spontaneous grass-herbaceous vegetation occurred in all variants (Fig. 1a), papilionaceans and some sown grasses being ousted from the sward, a mixture of meadow-grass (*Poa pratensis*), red fescue (*Festuca rubra*), timothy (*Phleum pratense*), rye-grass (*Lolium perenne*), and white clover (*Trifolium repens*), recommended by Sau (1983) for long-term pasture, was sown in 1984 in the first two variants to restore their initial sward. No fertilizers or herbicides were used in any period of the experiment. In the third variant (Fig. 1b) barley was restored for three years. Then (since 1988) once again the spontaneous herbaceous vegetation became permanent.

Starting from 1984 (beginning of the third decade), the dynamics of biomass formation was measured by the variants. The variants were distinguished on the basis of differences in the accumulation and/or elimination of aboveground organic matter. During both the third and fourth decades total grass-herbaceous biomass was returned to the site, after weighing, in variants I and IV which represent the objects of accumulative pedogenesis during 40 and 30 years, respectively. In variant II, aboveground phytomass was weighed and completely eliminated from the site during the last 20 years, i.e. from 1984. Variant III, initially characterized by summer barley, was (except for barley grains in 1984–87) accumulative (straw, weeds, and grasses returned) up to the end of the third decade. Then total aboveground grass-herbaceous phytomass was, analogously to variant II, weighed and eliminated. Thus, at the end of the fourth decade, the variants (in consecutive order in the Tables and Figures of this paper), according to the organic sources of pedogenesis were the following:

I – total sown grass-herbaceous biomass was returned and represented the driving force for pedogenesis during all 40 years;

IV – after the 10-year period without vegetation, a return of spontaneously formed biomass which acted as the driving force for pedogenesis during the last 30 years;

II – total sown lucerne-herbaceous biomass was returned during the first 20 years, while aboveground biomass was eliminated during the last 20 years; continuous elimination of the active part of the driving force for pedogenesis;

III – against the background of the annual vegetation, the perennial vegetation with intermittent accumulation and elimination of aboveground organic agents; elimination of one part of the driving force for pedogenesis prevailed during the last 10 years.

After continuous droughts in the late 1980s (Reintam 1998), mosses (*Rhytidiadelphus squarrosus*) spread intensively in the sward, and the herbaceous vegetation was strongly suppressed. Therefore moss control with ferrous vitriol ($FeSO_4 \cdot 7H_2O$) was performed in early 1998. Withered moss was gathered to avoid transfer of vitriol into soil beneath the moss cover.

Sampling

The morphological description and the sampling of the formed soils were carried out to a depth of 60 cm four times (early May of 1974, 1984, 1994, 2004) in a traditional way, well-known in soil science, separately for microfabric (1974 and 1984) investigations, for bulk density determination (in four replications using a steel cylinder of 50 cm^3), and for laboratory analyses. The solum dug by layers from the described profile was returned with the same layers and covered with a natural patch of turf taken from the same place to change the situation as little as possible. Figure 2 represents profiles from variant I in 1984, 1994, and 2004.

From the beginning of the third decade in early May 1984, the dynamics of the formation of aboveground phytomass was measured 3–4 times during each season of 20 years: in late May/early June, in late June/early July, in August/early September, and in October/early November. In about half of the years the growth of aboveground phytomass was inhibited by obvious moisture deficit after the third cutting of the yield, and the last sampling was impossible. Vegetation was cut from the entire area of the variants, weighed and sampled for determination of dry matter (in three replications) and for laboratory analyses. Raw phytomass was cut up and returned or removed according to the above described scheme. The obtained results were expressed in g m^{-2} of dry organic matter.

Analyses and calculations

Analyses were carried out in the laboratories of the Department of Soil Science and Agrochemistry, Estonian University of Life Sciences (former name Estonian Agricultural University), by a research assistant Raja Kährik, after the first and second decades also with participation of the students Virve Olvi and Tatyana Pogorelova. Fine earth less than 1 mm was used in 1964–94, and less than 2 mm in 2004. Samples for the determination of particle size were treated with sodium pyrophosphate to break down aggregates and carbonates. Sands were sieved and fractions finer than 0.05 mm were determined by pipette analysis (after the last decade *Pipette Apparatus Table Model 7 Samples*).

The cation exchange capacity and exchangeable bases were measured by percolation of a sample with ammonium acetate at pH 7.0 and expressed in cmol kg^{-1}. Exchangeable H^+ was ascertained in 0.5 M solution of Ca-acetate after Kappen. The total amounts (g kg^{-1}) of organic carbon and nitrogen were measured by the Tyurin and Kjeldahl volumetric methods, respectively (Ponomareva 1957). It is necessary to point out that the Anne method (van Ranst et al. 1999) is equivalent to the Tyurin method used. The group and fractional composition of humus was measured by the alternate acid-alkaline treatment according to the volumetric method of Tyurin–Ponomareva (Ponomareva 1957). The obtained results were expressed in the percentage of organic carbon. Group composition represents humic acids (H.a.), fulvic acids (F.a.), and humins known as the insoluble residue. The fractions within the groups are the following: 1a – free fulvic acids (only within the group of fulvic acids); 1 – humic and fulvic acids bound with mobile Fe and Al; 2 – humic and fulvic acids bound with Ca and Mg; 3 – humic and fulvic acids bound with immobile sesquioxides and clay.

The humic : fulvic ratio is an integral parameter of the maturity and mobility of humus as well as of humicity (>1) and/or fulvicity (<0.7). The ratio of the first to the second fraction demonstrates the relationship of the brown humic-fulvic complexes, bound with mobile sesquioxides, with the grey (black) complexes bound with alkaline earths. Decalcification with 0.05 M sulphuric acid represents a part of humus fractionation used to determine the second and the third fractions as well as the hydrolysate of 0.5 M sulphuric acid by extracting humus substances from the crystal structure of clay minerals (Ponomareva 1957). Carbonates were determined acidometrically. Tithionite-extractable (total pedogenic nonsiliceous) iron, oxalate-extractable

amorphous iron, aluminium, and silica were measured after Coffin and Tamm, respectively; iron activity was calculated after Schwertmann (van Ranst et al. 1999). The pH of both water and 1 M KCl suspensions was measured potentiometrically with the pH-meter *Jenway 3071*.

For the determination of the dry matter of aboveground phytomass, weighed raw samples in three replications were dried at 105 °C and weighed again after cooling. On the basis of the obtained data, total raw phytomass was recalculated as dry phyomass and expressed in g m^{-2} of dry organic matter. Milled dry material was used 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 measured by the method of wet digestion, respectively, with concentrated sulphuric acid after Kjeldahl, photocolorimetrically with ammonium vanadate, and with the help of flame photometry (Rodin et al. 1968). The amounts of ash and separate elements were calculated from particular phytomass and the percentage of the measured constituents. Total amounts were found as the sums of seasonal measurements.

The supply (sources) of soil constituents and soil properties were calculated on the basis of the particular thickness of the described layers (horizons) and of the measured bulk density. Requirements for the accuracy of sampling, laboratory techniques, and measurements were satisfied as for any reference profile (Batjes & van Engelen 1997). The statistically processed data include arithmetic mean (x), standard error of arithmetic mean (s_x), and coefficient of variation (V, %).

The air temperature and precipitation were measured by the Eerika Meteorological Station at the former Faculty of Agronomy, Estonian University of Life Sciences, in the neighbouring field of the Department of Botany and Grassland Husbandry (distance from our experiment about 200 m). The method of Walter (1955) was applied to the characterization of climate with the help of climatograms (Fig. 3). The idea of this method consists in the simultaneous graphic representation of air temperature (t, °C) and precipitation on two scales: in the first case 20 and in the other case 30 mm of precipitation corresponds to 10 °C. Precipitation curves above the temperature curve indicate sufficient moisture for normal development of vegetation. Walter (1955) called this climate (weather) "advective". Precipitation curves below the temperature curve show moisture deficiency and droughts within the vegetation period. Such a climate (weather) was called by Walter as "radiational" and/or "advective with radiational elements". According to Walter, especially severe droughts are characteristic of the second (10 °C = 30 mm) scale of temperature/precipitation relationships. Although the multiannual average (Reintam 1998) reveals advectivity of weather at Eerika, in fact, among 21 years only four (1985, 1991, 1998, and 2001) were advective (Fig. 3). One or several radiational spaces in time were characteristic of all other years.

RESULTS AND DISCUSSION

Biomass accumulation

Like in the third decade, aboveground phytomass was measured during the fourth decade (Table 1). On the basis of these results and using relevant literature data (Arvisto 1970, 1971; Grishina 1974; Sau 1979; Sau et al. 1980), the possible extent of humification was calculated as earlier (Reintam & Pogorelova 1986, 1987; Reintam 1995, 1998). Differences in the absolute figures of aboveground dry organic matter were as large as 25–44% (one-third) between the variants with multiannual return (I, IV) and removal (II, III). The spontaneous vegetation of the initial zero variant (IV in 1964–73) was on a par with the initial pasture sward (I) already by the end of the second decade, exceeding at present the latter by even about 20%, i.e. twice as much as ten years ago. Complete removal of aboveground grass-herbaceous phytomass has resulted in a two- to threefold decrease in possible pedogenetic agents in comparison with the variants with phytomass restoration. It is possible that the ratio of aboveground to underground phytomass diminished as a result of the increase in root mass and the decrease in aboveground mass in the process of its continuous removal. Such a phenomenon has been reported before from neighbouring experimental areas with grasses (Sau 1983; Viiralt & Kabanen 1985).

The sources of possible humification during earlier decades were many times larger (Table 1). After adding up all possible amounts, the differences between the variants decreased but still exceeded the differences between the actual measured accumulations of organic carbon in the soil during 40 years. During the whole period of 40 years the progress of soil formation could have been induced (at a significance level of 10%) by residues, expressed in organic carbon of plant origin, which was able to humify in the amount of 1.3–2.0 and 0.9–1.4 kg m^{-2} in the case of their complete restoration and in the case of prevailing partial removal, respectively (Table 1). As these characteristics are quite similar to those reported for previous decades, the initial literature data used for such calculations prove to be reliable and significant as well as comparable with those

(a)

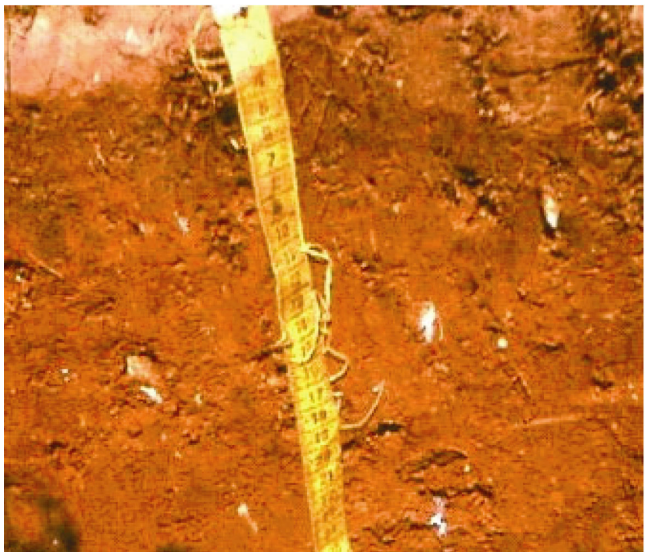
(b)

Fig. 1. The experimental area at Eerika in 1984: (a) from front to back: variants I, II, III, and IV; (b) the author standing next to variant III (barley).

(a)

1984

(b)



1994

(c)

2004

Fig. 2. Calcaric Cambisol profiles under grass-herbaceous sward in 1984 (a), 1994 (b), and 2004 (c) when the layer between 10 and 20(30) cm had dried to the discontinuous capillary moisture level, which caused the compactness and a lighter value of chroma there.

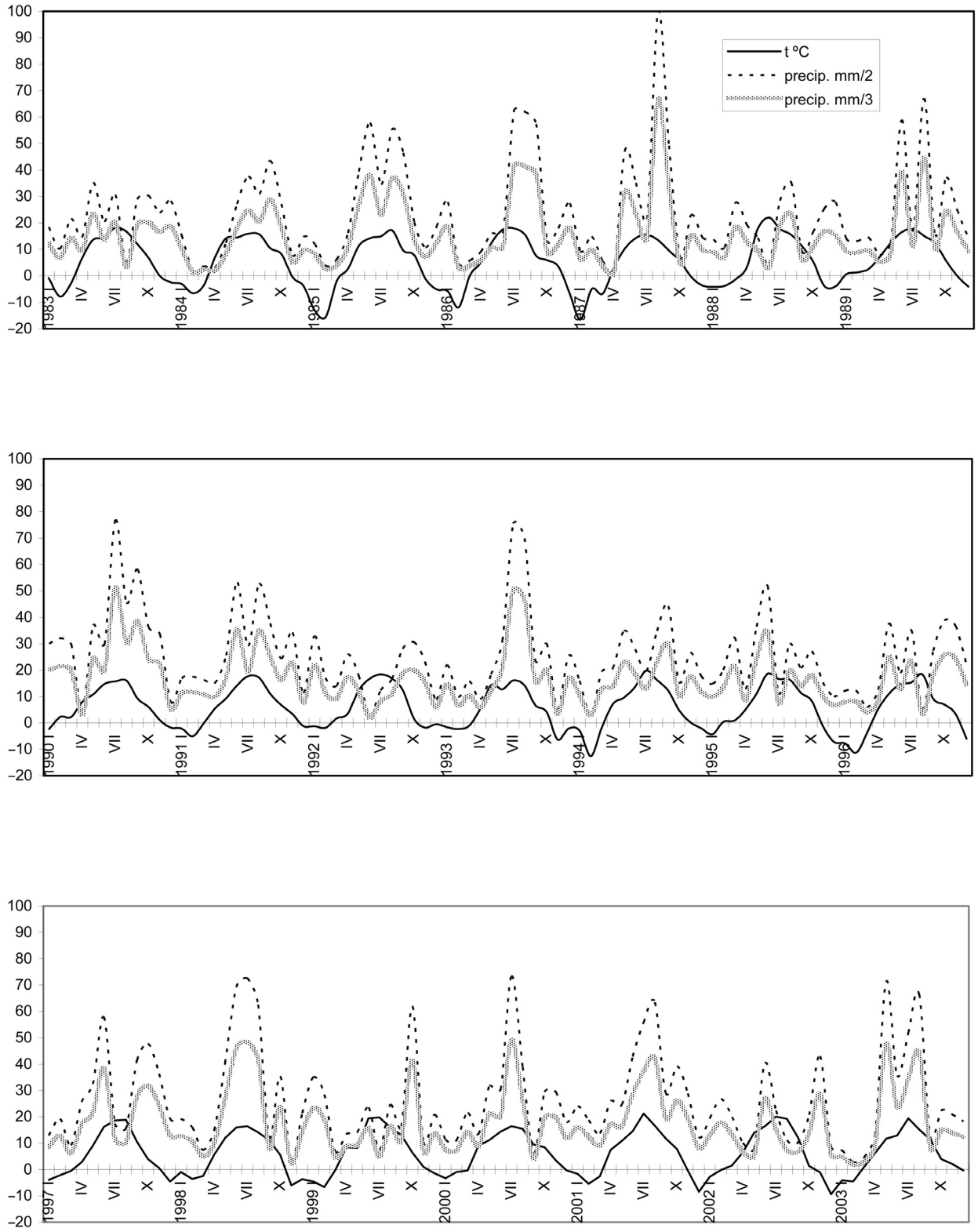


Fig. 3. Climatogram for 1983–2003 constructed after Walter (1955): *t* °C, air temperature; precip. mm/2, precipitation per 10 °C = 20 mm; precip. mm/3, precipitation per 10 °C = 30 mm.

Table 1. Accumulation of organic residues in the soil in 1994–2003, and before, g m^{-2}

Characteristics	I	IV	II	III
Measured aboveground dry phytomass	3351	4154	2311	2518
According to the ratio of above- to underground dry phytomass 1 : 1 (Sau 1979; Sau et al. 1980), accumulation of 30% of root residues (Grishina 1974) in soil	1005	1246	693	755
Possible humification of root residues up to 50%	503	623	347	378
Possible humification of aboveground mass up to 10% (Arvisto 1970, 1971)	335	415	0	0
Total possible humification	838	1038	347	378
Total possible humification in 1964–93 (Reintam & Pogorelova 1986, 1987; Reintam 1995)	3702	2532	2741	2149
Total possible humification during 40 years (1964–2003)	4540	3570	3088	2527
Total possible accumulation of C of plant origin at the average C content of 40% (Viiralt 2005)	1816	1428	1235	1011
Measured accumulation of organic C by the end of 40 years	3289	3822	3868	2807

by other authors (Scurlock et al. 2002; Pucheta et al. 2004). As earlier (Reintam 1998), the yearly and seasonally fluctuating level of production is correlated with climatic fluctuations in years and seasons (Fig. 4). In more precipitation-rich years of 1998, 2001, and 2003 the vegetation lasted up to October, and more than 50% of aboveground production was formed during July and August. Relatively slight fluctuations during about the first month of the vegetation period in different years demonstrate the significant impact of winter precipitation as well as summer drought on the dynamics of the formation of biological agents for pedogenetic processes (Figs 3 and 4).

During the fourth decade, 284–346 g m^{-2} of the ash elements and 73–88 g m^{-2} of the nitrogen cycled within the plant–soil system (variants I, IV) against the background of the permanent return of the aboveground yield to the site. For phosphorus and potassium, these amounts were 9–10 and 92–118 g m^{-2}, respectively. At the same time, yield removal (variants II, III) resulted in the impoverishment of the site by 186–206, 52–55, 6–7, and 58–64 g m^{-2} of total ash, nitrogen, phosphorus, and potassium, respectively. During 1984–2003, 6.0 Mg ha^{-1} of ash elements, 1.4 Mg ha^{-1} of both nitrogen and potassium, and 0.24 Mg ha^{-1} of phosphorus were carried out of the turnover of substances with an eliminated dry mass of 59.9 Mg ha^{-1}. The result of the removal of aboveground organic matter was impoverishment of soil sources by 101 kg Mg^{-1} of ash elements, 24 kg Mg^{-1} of both nitrogen and potassium, and 4 kg Mg^{-1} of phosphorus.

Accumulation of organic carbon

Against the background of yield removal, the decrease in aboveground phytomass appears to be accompanied by a larger increase in the root system than was calculated (Table 1). Therefore differences in the real accumulation of organic carbon under the herbaceous sward do not exceed 15%, being higher only against the background of initial and intermediate annual crops. Although these differences showed a trend of decrease in the thin 5–8 cm top during the fourth decade, they were preserved within the entire 60 cm solum (Tables 2 and 3). Like at the beginning of pedogenesis 40 years ago (Reintam 1982) and at the end of the third decade (Reintam 1995), a continuous humus-accumulative process was characteristic of soil formation against all backgrounds of the experiment. During four decades this accumulation amounted to 4.8–7.7 and 2.6–3.9 g m^{-1} of organic carbon per 1 cm per year in the layers of 5 and 20 cm, respectively. Against the background of yield elimination, the loss of carbon at the end of the third decade was now covered by increased accumulation in the fourth decade as a result of which the total process, wavy in origin, became accumulative.

It means that the increase in the stabilization of humus compounds progressed. Humification of the root residues in deep layers also tends to continue, resulting in the enrichment of the solum in carbon and nitrogen even up to 60 cm, although a quite significant portion of organic matter should belong to microbial mass there (Tables 2 and 3). The cyclic oxidational decomposition of the unstable carboxydes and/or carbohydrates of humus substances, rapid hydrolysis of the formed microbial matter, and deamination of humus molecules, as well as the cyclic synthesis of stable humins and humic compounds (Flaig 1971; Martin & Haider 1971), are due to changes in such cyclic carbon–nitrogen relationships (Table 3).

The wavy character of mean annual increments in decades confirms the periodicity of mineralization and humification described by Sau (1979, 1983), with an alternation of 6–7-year periods in the primary formed topsoil. During the 20-year period of soil formation, 37–43% of pedogenetic organic carbon and 50–75% of nitrogen were contained in the top 5 cm layer; ten years later these features accounted for 40–52 and 33–35(61)%, respectively (Reintam 1995). At the end of 40 years, 39–65% of organic carbon and (26)34–38% of nitrogen were accumulated in the topsoil of 7–10 cm, while already 60–79% of carbon and 48–53% of nitrogen were contained in the layer of 20 cm. Ten years earlier only 2–8% of carbon occurred deeper than 40 cm, now, however, 9–17% of carbon and 22–26% of nitrogen are contained at such depths. Also fine roots were found between nutty aggregates. Thus, the process of humus accumulation has developed quantitatively in the topsoil and has spatially penetrated deeper into till. Also annual increments have increased by decades (Table 3). In most cases the smallest amounts characterize the background with annual crops at the early and intermediate stages of the study.

The accumulation of humus was accompanied with the formation of new crumble and granulous macro- and microaggregates, as well as with the decrease in bulk density of the topsoil (Table 4), as a consequence of which an upward growth of the humus profile took place (Reintam 1997). In spite of yearly fluctuations, this phenomenon was more obvious in the topsoil where aboveground phytomass was returned; however, in the entire solum, where phytomass was removed, and owing to hop lucerne and some perennial weeds, the root system could have been better developed. The problem

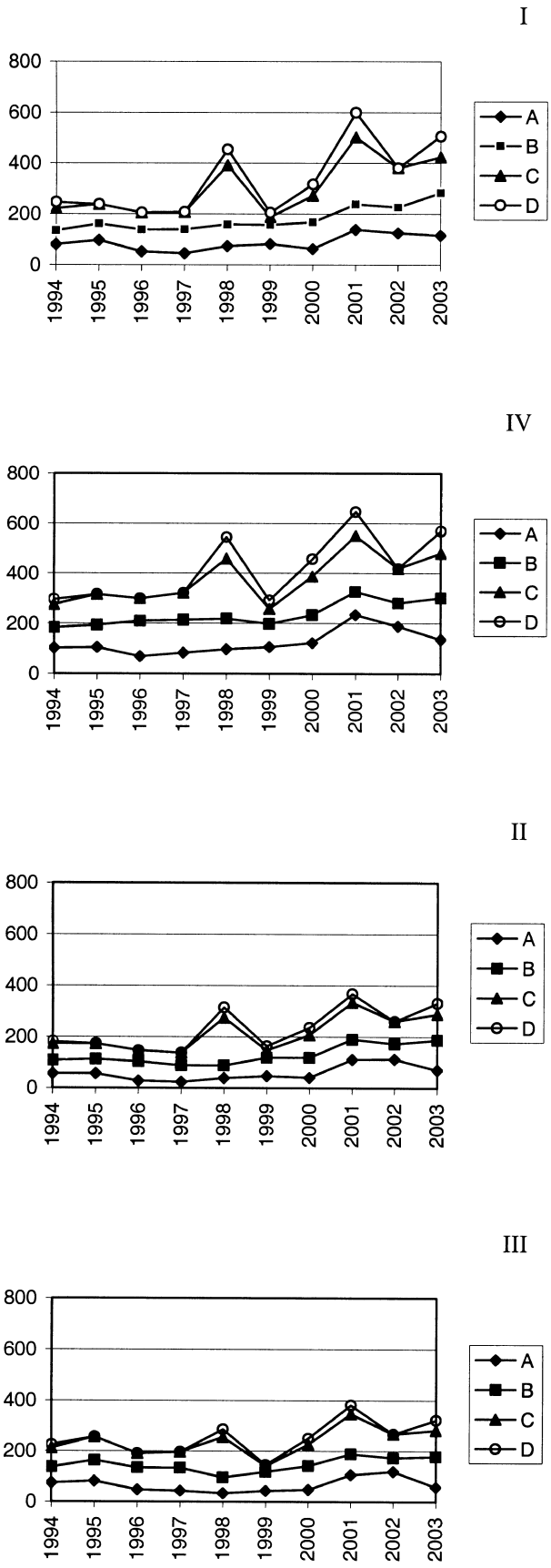


Fig. 4. Aboveground phytomass, g m^{-2} of dry matter: variants I, IV, II, III, see also text pp. 66–67; A, late May/early June; B, late June/early July; C, August/early September; D, October/early November (total vegetation period).

Table 2. Organic carbon and nitrogen accumulated in pedogenesis during 40 years, g m^{-2}

Horizon and depth, cm	I			IV			II			III		
	C	N	C/N	C	N	C/N	C	N	C/N	C	N	C/N
A 0–5(8)	1549	128	12.1	1311	103	12.7	1920	163	12.8	1341	130	10.3
5–10	997	100	10.0	926	94	9.8						
Bw (7)10–20	548	83	6.6	462	99	4.7	1129	81	14.0	699	109	6.4
BC 20–30	195	88	2.2	619	71	8.8	338	51	6.7	480	80	6.0
30–40	256	68	3.0	412	72	5.8	439	68	6.5	326	49	6.7
40–50	189	69	2.8	383	87	4.4	255	51	5.0	310	82	3.8
50–60	171	68	2.5	325	51	6.3	403	50	8.0	267	50	5.3
0–20	3094	311	10.0	2699	296	9.1	3049	244	12.5	2040	239	8.5
20–40	451	156	2.9	1031	143	7.2	777	119	6.5	806	129	6.2
40–60	360	137	2.6	708	138	5.1	658	101	6.5	577	132	4.4
0–60	3905	604	6.7	4438	577	7.7	4484	464	9.7	3423	500	6.8

Table 3. Accumulation and dynamics of organic carbon and nitrogen, g m^{-2}

Variant and depth, cm		Organic C			N			Annual increment of C			Annual increment of N	
		1984	1994	2004	1984	1994	2004	1984–1994	1994–2004	1984–2004	1984–1994	1994–2004
I	0–20	1190	2125	3094	93	240	311	93.5	96.9	95.2	14.7	7.1
	20–40	370	184	451	70	29	156	−18.6	26.7	4.1	−4.1	12.7
	40–60	50	124	360	94	32	137	7.4	23.6	15.5	−6.2	10.5
	0–60	1610	2433	3905	257	301	604	82.3	147.2	229.5	4.4	30.3
IV	0–20	1700	1496	2699	64	124	296	−20.4	120.3	50.0	6.0	17.2
	20–40	130	194	1031	35	35	143	6.4	83.7	50.1	0.0	10.8
	40–60	60	147	708	39	66	138	8.7	56.1	32.4	2.7	7.2
	0–60	1890	1837	4438	138	225	577	−5.3	260.1	127.4	8.7	35.2
II	0–20	1570	1223	3049	122	116	244	−34.7	182.6	74.0	−0.6	12.8
	20–40	210	256	777	33	51	119	4.6	52.1	28.4	1.8	6.8
	40–60	60	33	658	21	34	101	−2.7	62.5	29.9	1.3	6.7
	0–60	1840	1512	4484	176	201	464	−32.8	297.2	132.2	2.5	26.3
III	0–20	1040	1555	2040	170	107	239	51.5	48.5	50.0	7.7	13.2
	20–40	170	107	806	1	0	129	−6.3	69.9	31.8	−0.1	12.9
	40–60	110	67	577	0	0	132	−4.3	51.0	23.4	0.0	13.2
	0–60	1320	1729	3423	61	137	500	40.9	169.4	105.2	7.6	36.3

connected with the loosening of planted topsoil and some compaction of deeper layers can be explained by some human impacts on the formation of the density relationships within till used (Hartge 1994).

As explained ten years ago (Reintam 1995), weathering of carbonates characterizes pedogenesis on calcareous parent till from the early stages of the process. This definitely leads to the leaching of carbonates but also to an intensive breakdown of the calcareous skeleton and enrichment of fine earth with carbonates derived partly even from pebble and/or gravel (Table 5). Except for the variant with the pasture sward and permanent return of the yield (I), the last phenomenon seems to be more obvious during the last two decades in the conditions of intensified biological activity and increase in the accumulation of organic carbon as an agent for pedogenesis. Leaching tends to occur within the topsoil to a depth of 20 cm. The upward and two-directional movement of mobilized carbonates of skeletal origin during alternative droughts and moistening cannot

Table 4. Bulk density, Mg m^{-3}

Variant	Depth, cm	1974		1984		1994		2004	
		$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %
I	0–5	1.49 ± 0.03	4.5	1.28 ± 0.09	4.7	1.42 ± 0.03	4.7	1.16 ± 0.07	12.1
	5–10	1.74 ± 0.02	2.9	1.60 ± 0.03	3.8	1.42 ± 0.03	4.7	1.33 ± 0.07	11.3
	10–20	1.82 ± 0.04	5.0	1.70 ± 0.04	4.7	1.74 ± 0.05	6.5	1.66 ± 0.02	3.0
	20–30	1.74 ± 0.03	5.2	1.75 ± 0.04	4.6	1.69 ± 0.12	14.8	1.77 ± 0.08	9.6
	30–40	1.70 ± 0.03	4.7	1.70 ± 0.03	3.5	1.71 ± 0.02	2.2	1.71 ± 0.06	6.4
	40–60	1.71 ± 0.03	3.5	1.71 ± 0.03	3.5	1.71 ± 0.01	0.6	1.71 ± 0.01	1.2
IV	0–5	1.57 ± 0.06	7.0	1.18 ± 0.02	3.4	1.60 ± 0.07	9.4	1.15 ± 0.08	13.9
	5–10	1.73 ± 0.01	1.2	1.40 ± 0.03	4.3	1.68 ± 0.02	2.7	1.18 ± 0.05	9.3
	10–20	1.73 ± 0.03	2.9	1.78 ± 0.04	4.5	1.80 ± 0.03	3.4	1.65 ± 0.04	4.8
	20–30	1.75 ± 0.05	8.0	1.74 ± 0.04	4.6	1.79 ± 0.03	2.8	1.77 ± 0.02	1.7
	30–40	1.73 ± 0.04	5.2	1.71 ± 0.03	3.5	1.71 ± 0.02	2.3	1.79 ± 0.05	5.0
	40–60	1.71 ± 0.02	1.8	1.71 ± 0.03	3.5	1.71 ± 0.02	2.3	1.71 ± 0.02	1.8
II	0–5	1.46 ± 0.04	6.2	1.23 ± 0.03	4.9	1.38 ± 0.10	15.0	1.27 ± 0.02	2.4
	5–10	1.78 ± 0.06	7.9	1.55 ± 0.03	3.9	1.59 ± 0.03	4.7	1.47 ± 0.03	4.0
	10–20	1.85 ± 0.01	1.6	1.87 ± 0.05	5.3	1.77 ± 0.01	0.6	1.68 ± 0.03	3.6
	20–30	1.85 ± 0.03	3.8	1.75 ± 0.04	4.6	1.72 ± 0.08	9.0	1.69 ± 0.07	8.3
	30–40	1.73 ± 0.03	3.5	1.59 ± 0.04	5.0	1.70 ± 0.03	3.9	1.69 ± 0.00	0.6
	40–60	1.66 ± 0.03	3.6	1.70 ± 0.03	3.4	1.70 ± 0.03	3.9	1.70 ± 0.02	2.9
III	0–5	1.67 ± 0.05	6.0	1.31 ± 0.06	9.2	1.55 ± 0.06	8.4	1.33 ± 0.07	10.1
	5–10	1.73 ± 0.03	4.0	1.64 ± 0.04	4.9	1.64 ± 0.02	1.8	1.50 ± 0.04	5.3
	10–20	1.74 ± 0.02	2.3	1.63 ± 0.03	3.8	1.71 ± 0.02	2.0	1.68 ± 0.01	1.8
	20–30	1.76 ± 0.02	2.8	1.82 ± 0.03	3.5	1.68 ± 0.03	4.1	1.60 ± 0.03	3.7
	30–40	1.69 ± 0.02	3.0	1.66 ± 0.05	5.9	1.75 ± 0.05	6.1	1.63 ± 0.07	8.6
	40–60	1.66 ± 0.01	1.8	1.70 ± 0.04	4.7	1.70 ± 0.07	8.1	1.67 ± 0.05	6.6

Table 5. Amount of $CaCO_3$ in fine earth, kg m^{-2}

Variant	Depth, cm	Year					Average during 40 years	
		1964	1974	1984	1994	2004	$x \pm s_x$	V, %
I	0–5	5.8	5.3	4.5	4.9	3.3	4.5 ± 0.4	19
	0–20	23.3	18.0	22.6	15.4	17.4	18.4 ± 1.5	17
	0–60	69.8	44.6	37.1	29.0	44.4	38.8 ± 3.7	19
IV	0–5	5.8	5.6	4.5	6.1	3.5	4.9 ± 0.6	24
	0–20	23.3	27.6	25.1	28.4	22.7	25.9 ± 1.3	10
	0–60	69.8	70.4	81.6	83.1	86.4	80.4 ± 2.1	5
II	0–5	5.8	5.0	4.1	4.4	6.0	4.9 ± 0.4	17
	0–20	23.3	24.4	22.9	22.4	22.3	23.0 ± 0.5	4
	0–60	69.8	61.8	52.4	60.6	74.5	62.3 ± 4.6	15
III	0–5	5.8	5.5	6.8	6.9	7.3	6.6 ± 0.4	12
	0–20	23.3	25.3	29.1	22.9	26.5	25.9 ± 1.3	10
	0–60	69.8	67.3	80.6	43.9	85.5	69.3 ± 9.3	27

be excluded, either. Large yearly differences within variant III could be caused by the varieties in bulk density under the alternation of annual and perennial vegetation.

Qualitative composition of accumulated organic matter

Compared with its former status (Reintam 1982, 1995; Reintam & Pogorelova 1986, 1987), the group and fractional composition of humus has become more stable (Table 6), although certain fluctuations by decades have not disappeared (Table 7). Fulvic compounds, extractable by 0.5 M sulphuric acid, showed a decrease everywhere in the last decade. This tends to demonstrate the progress of humus against the background of an increased polycondensation and transformation of these, as well as perhaps of some other fulvic fractions, into humic complexes, especially in the stable form. Such a complicated process was described some decades ago by Aleksandrova (1980) in connection with alternating mild and severe winters. An in-depth increase in stable humic acids, bound with clay and immobile sesquioxides, is accompanied by an evident trend of the downward development of the A-horizon at the expense of the weathered top of till. In spite of the weathering of skeletal carbonates and enrichment of fine earth with consequent products (Table 5), humic compounds bound with alkaline earths are often lacking, or are only present in the thin topsoil (Tables 6 and 7). In spite of the possible presence of living microbial biomass in the composition of free fulvic acids (Beyer et al. 1991), the relative stability of active R_2O_3-fulvates is evident in the conditions of base saturation and neutral to slightly alkaline reaction. The transformation of Ca-humates into humins appears to be favoured there.

Changes in the dynamics of humus composition are also determined by the formation of R_2O_3-fulvic complexes at the expense of the transformation of Ca-humic-fulvic complexes. At the end of the first decade, it was established that the humification of organic residues began with the intensive formation of free fulvic acids (Reintam 1982). By the end of 40 years, the amount of free fulvic acids had clearly decreased by decades, ensuring their sufficient weathering–pedogenetic activity and transformation into more complicated humus substances.

During the last decade the mobilization and accumulation of both amorphous and total pedogenic nonsiliceous iron, characteristic of pedogenetic weathering

Table 6. Composition of 40-year-old humus in percentage per total organic carbon

Characteristics*	Variant and depth, cm											
	I			IV			II			III		
	0–5	5–10	10–20	0–5	5–10	10–20	0–8	8–20	20–30	0–7	7–20	20–30
Org. C	26.7	15.0	3.3	22.8	15.7	2.8	18.9	5.6	2.0	14.4	3.2	3.0
N	2.2	1.5	0.5	1.8	1.6	0.6	1.6	0.4	0.3	1.4	0.5	0.5
C/N	12.1	10.0	6.6	12.7	9.8	4.7	11.8	14.0	6.7	10.3	6.4	6.0
H.a. 1	4.8	4.4	2.3	7.1	6.6	1.6	4.7	1.2	1.0	8.5	1.0	0.0
2	2.2	2.0	0.0	0.7	1.7	0.0	2.2	0.0	0.1	2.3	1.6	0.9
3	4.9	4.8	6.8	5.5	5.8	7.1	4.6	5.3	2.0	3.8	7.3	3.4
Σ	11.9	11.2	9.1	13.3	14.1	8.7	11.5	6.5	3.1	14.6	9.9	4.3
F.a. 1a	8.2	7.0	12.6	6.5	9.1	4.3	5.0	6.7	1.8	7.3	6.5	3.9
1	13.6	16.6	0.2	18.3	13.5	7.1	6.7	6.0	8.5	6.0	5.2	0.1
2	9.6	1.8	2.5	1.3	1.8	5.0	8.0	4.4	0.7	8.5	7.0	0.5
3	2.6	10.3	6.4	3.8	3.8	10.0	6.6	6.0	6.7	6.5	10.1	5.0
Σ	34.0	35.7	21.7	29.9	28.2	26.4	26.3	23.1	17.7	28.3	28.8	9.5
0.5 M H_2SO_4 extract	9.4	9.1	17.7	10.0	8.0	9.6	8.5	14.6	15.6	4.9	21.0	14.2
Total soluble	55.3	56.0	48.5	53.2	50.3	44.7	46.3	44.1	36.4	47.8	59.7	28.0
Insoluble	44.7	44.0	51.5	46.8	49.7	55.3	53.7	55.9	63.6	52.2	40.3	72.0
H.a./F.a.	0.35	0.31	0.42	0.44	0.50	0.33	0.44	0.28	0.18	0.52	0.34	0.45
1.fr/2.fr.	1.56	5.53	1.00	12.7	5.74	1.74	1.12	1.64	11.8	1.34	1.07	0.07

* The content of organic C and N in g kg^{-1}; H.a. – humic acids, F.a. – fulvic acids.

Table 7. Some indices of the state of humus during 40 years

Year	Variant and depth, cm											
	I			IV			II			III		
	0–5	5–10	10–20	0–5	5–10	10–20	0–5	5–10	10–20	0–5	5–10	10–20
	Degree of humification (after Grishina & Orlov 1977)											
1974	11	11	27	8	x	x	0	0	x	4	x	x
1984	16	16	9	13	10	17	18	14	13	14	14	13
1994	14	5	6	8	6	4	10	6	7	9	7	10
2004	12	11	9	13	14	9	12	6	3	15	10	4
	Role of active humic acids (1st fraction), percentage of total humic acids											
1974	46	43	21	17	x	x	42	0	x	75	x	x
1984	39	50	28	53	32	23	40	30	41	33	39	33
1994	54	0	0	42	5	0	45	0	0	54	11	0
2004	40	39	25	53	47	18	41	30	19	58	34	0
	Role of stable humic acids (3rd fraction), percentage of total humic acids											
1974	6	0	0	0	x	x	0	0	x	0	x	x
1984	45	46	72	47	65	77	34	35	59	67	61	67
1994	25	100	100	56	87	100	53	94	33	46	89	70
2004	41	43	75	41	41	82	40	62	83	26	50	74
	Solubility of humus, percentage of total organic carbon											
1974	74	88	94	68	x	x	70	68	x	71	x	x
1984	56	66	51	56	32	76	57	44	74	58	59	96
1994	56	54	84	54	72	42	56	49	53	45	54	78
2004	55	56	49	53	50	45	46	45	44	48	54	60
	Extracted by 0.5 M H_2SO_4, percentage of total organic carbon											
1974	18	23	17	22	x	x	22	16	x	27	x	x
1984	13	16	13	14	9	16	11	8	11	18	17	21
1994	13	23	33	17	20	17	16	21	14	14	23	14
2004	9	9	18	10	8	10	9	15	16	5	21	14
	1st fraction of humic and fulvic acids : 2nd fraction of humic and fulvic acids											
1974	0.6	0.3	0.2	0.3	x	x	0.7	0.2	x	0.8	x	x
1984	1.2	0.5	0.6	1.8	1.9	0.5	1.9	0.9	0.6	0.5	0.7	0.3
1994	1.9	5.2	0.1	51.3	0.2	6.4	5.0	16.0	1.6	27.5	6.6	0.3
2004	1.6	5.5	1.0	12.7	5.7	1.7	1.1	1.6	11.8	1.3	1.1	0.1
	Humic acids : fulvic acids											
1974	0.3	0.2	0.6	0.2	x	x	0.1	0.0	x	0.1	x	x
1984	0.6	0.5	0.3	0.5	0.7	0.4	0.6	0.7	0.3	0.5	0.5	0.2
1994	0.5	0.2	0.1	0.3	0.3	0.1	0.8	0.3	0.2	0.2	0.3	0.2
2004	0.4	0.3	0.4	0.4	0.5	0.3	0.4	0.3	0.2	0.5	0.3	0.4

x, not determined.

of ferri- and alumosilicates and argillization, decreased in the variants where calcareousness of fine earth had increased (Tables 5, 8, and 9). Nevertheless, in neutral and base-saturated conditions, R_2O_3-humic-fulvic complexes (instead of RO-humic-fulvic complexes of the first two decades) became prevalent throughout the solum (Tables 6 and 7). The situation appears to be similar to that described in acid conditions (Kleber et al. 2005; Eusterhues et al. 2005) where organic matter is also protected by the oxalate-soluble fractions of sesquioxides.

The same is also observed in the composition of decalcinate (Table 10). According to Ponomareva (1964), such relationships of mobile iron and aluminium with free fulvic carbon do not allow formation of removable complexes of sesquioxides, and so their accumulation in situ must have been favoured. The downward

Table 8. Amount and dynamics of oxalate-extractable Fe, Al, and Si, g m^{-2}

Variant	Depth, cm	1974			1984			1994			2004		
		Fe	Al	Si	Fe	Al	Si	Fe	Al	Si	Fe	Al	Si
I	0–5	115	47	28	98	20	54	134	49	36	75	41	12
	5–10	145	55	20	106	25	34	159	48	35	93	60	33
	10–20	344	125	76	345	36	151	356	117	119	266	183	66
	20–30	353	129	49	428	83	147	354	72	80	248	159	124
	30–40	357	126	40	309	81	151	299	127	120	188	137	68
	40–60	669	253	144	589	51	166	645	253	271	514	308	137
IV	0–5	143	50	37	144	31	30	196	38	78	92	46	17
	5–10	133	55	40	127	26	39	176	18	63	100	65	18
	10–20	242	119	154	199	75	199	234	86	151	198	149	99
	20–30	246	112	66	389	64	114	263	66	192	177	177	124
	30–40	290	119	73	347	72	96	227	72	56	215	161	90
	40–60	574	217	144	551	152	33	492	149	151	415	364	243
II	0–5	112	46	14	69	13	43	92	55	32	95	76	6
	5–10	149	57	58	135	16	73	117	46	30	107	90	28
	10–20	310	117	130	248	69	131	359	122	17	252	218	117
	20–30	323	92	43	428	111	155	349	73	48	237	169	68
	30–40	339	110	48	289	101	104	404	126	159	237	186	339
	40–60	789	246	124	760	144	460	760	108	302	473	457	338
III	0–5	111	53	31	101	21	25	157	37	65	86	64	20
	5–10	97	46	32	149	30	54	178	38	78	95	86	38
	10–20	243	110	81	182	26	99	290	60	140	202	202	101
	20–30	271	93	66	483	67	94	282	98	157	208	176	112
	30–40	307	116	103	220	62	116	367	74	147	228	228	98
	40–60	696	246	248	760	180	333	713	270	302	380	329	66

Table 9. Amount and dynamics of pedogenetic nonsiliceous Fe in the solum of 50 cm, g m^{-2}

Variant	Pedogenic amount			Average annual pedogenic increment			
	1974	1994	2004	1964–1974	1974–1994	1994–2004	1974–2004
I	1279	3742	2312	127.9	123.0	–143.0	34.4
IV	126	2352	2668	12.6	111.1	31.6	84.7
II	650	2961	3426	65.0	115.3	46.5	92.5
III	336	3886	1659	33.6	177.5	–222.7	44.1

Table 10. Composition of decalcinate after 40 years, g kg^{-1}

Constituent	Variant and depth, cm											
	I			IV			II			III		
	0–5	5–10	10–20	0–5	5–10	10–20	0–8	8–20	20–30	0–7	7–20	20–30
Org. C	2.20	1.00	0.40	1.50	1.40	0.10	0.90	0.70	0.01	1.10	0.20	0.10
Fe	0.98	0.54	0.23	0.91	0.89	0.41	0.75	0.52	0.34	0.64	0.28	0.28
Al	0.17	0.25	0.16	0.40	0.34	0.13	0.45	0.36	0.24	0.45	0.18	0.17
Ca	9.00	8.40	7.00	10.20	10.40	11.80	9.20	10.30	8.80	11.80	10.30	11.10
Mg	3.30	3.40	3.00	3.80	4.10	3.90	3.70	4.00	3.30	4.70	3.90	3.90
Fe/C	0.45	0.54	0.58	0.61	0.64	4.00	0.83	0.74	34.0	0.58	1.40	2.80
Al/C	0.08	0.25	0.40	0.27	0.24	1.30	0.50	0.51	24.0	0.41	0.90	1.70

migration of RO-fulvates appears to be inhibited due to their transformation into immovable R_2O_3-humic-fulvic complexes in the conditions of high pH and base saturation. Neosynthesis of secondary illite and chlorite from the nonsiliceous products of weathering is possible, although under these conditions the formation of illite and smectite could first of all take place by the weathering of mica only. Partial leaching of alkaline earths, extractable in decalcinate, in the form of simple solutions cannot be excluded. Moreover, stronger organic bonds with illite tend to favour the formation of stable organo-mineral complexes and aggregates (Denef & Six 2005). As a result, differences in the quality of humus in the first 20 years between variants have levelled. According to Dell'Abate et al. (2002), the rate of humification (the percentage of humic-fulvic complexes of organic carbon) within variants altogether was at the end of 40 years 43.2±1.3% in the A-horizon and 33.5±2.2% in the Bw-horizon formed. The degree of humification (percentage of humic-fulvic complexes of soluble humus) was 83.9±2.5 and 68.4±6.2%, respectively.

Texture and exchange properties

Organic impacts on the mineral constituents of reddish-brown till resulted in the progress of argillization in situ and a slight decrease in clay within the thin top (Table 11). Ten years ago (Reintam 1997) it was shown that the pedogenetic redistribution of fractions indicated accumulation of silt and clay in the middle part of the profiles formed as a result of the breakdown of sand. Also the remnant accumulation of its coarse and medium particles was described. Use of the fractions of sand and coarse silt as indicators resistant to weathering and pedogenesis showed the upward growth of the solum as well as the slightly developed clay-and-silt-accumulative process. Argillization in situ has led to the uniform development of visible and analytically determinable cambic properties almost to the same extent throughout the profiles. Against the background of this process, a slight lessivage of fine-dispersed particles and their chemical constituents was registered in the topsoil within about 20 cm. These phenomena have continuously developed during the last decade, while differences between the variants have diminished. Therefore, instead of the granulometric composition of variants, Table 11 provides the average data of all of them taken together.

Morphological features of clay eluviation, formation of evident clayskins, and presence of argillic properties are still lacking. At the time of sampling in 2004, the value of chroma (5YR4/6) at a depth of about 10–30 cm was a little higher than at a depth below 30 cm (5YR4/5) not because of the removal of reddish-brown clay particles but because of seasonal drying-up to a status between the permanent wilting point and discontinuous capillary moisture (Fig. 2). At that time the solum above and below the dried-up layer was characterized by the presence of moisture between discontinuous capillary and field capacities. Analyses show that apparent lessivage tends to be significant within the thin ochric epipedon close to the very surface where maximum humus formation and accumulation have taken place. It has been demonstrated earlier that the thin surface layer is seasonally subjected to weak reductomorphic processes and frost impacts as a result of which some topsoil

Table 11. Average texture of fine earth of all variants after 40 years, %

Fractions, μm	Horizon and depth, cm													
	A 0–5		A/Bw 5–10		Bw 10–20		BC 20–30		BC 30–40		BC 40–50		BC 50–60	
	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %
1000–500	6.3±0.6	20	6.4±0.5	16	5.5±0.4	13	4.5±0.4	16	4.9±0.2	9	5.8±0.3	10	5.9±0.6	20
500–250	13.7±0.2	3	13.0±0.3	4	12.9±0.2	3	11.3±0.3	5	11.8±0.4	7	10.9±0.5	8	11.5±0.5	9
250–100	30.7±0.7	5	29.4±0.9	6	29.3±0.3	2	30.3±0.6	4	30.1±0.4	3	30.5±0.6	4	29.8±0.7	4
100–50	13.4±0.3	5	13.9±0.5	7	13.8±0.5	7	15.0±0.4	5	13.8±0.7	10	13.0±0.2	4	13.4±0.1	1
50–20	11.2±0.8	16	10.7±0.6	10	11.3±0.6	11	11.3±1.3	23	12.3±0.8	14	12.8±0.6	5	13.1±1.6	24
20–5	10.5±0.8	15	11.6±2.0	25	10.3±0.2	4	11.0±0.3	24	9.7±0.2	4	10.1±0.4	7	9.3±1.1	24
5–2	5.4±0.2	7	3.5±0.5	30	3.5±0.5	28	3.7±0.4	19	4.2±0.3	15	4.1±0.1	3	4.2±0.5	25
<2	8.8±0.6	15	11.5±1.7	30	13.4±0.7	11	12.9±1.1	17	13.2±0.6	9	12.8±0.7	11	12.8±0.3	5

properties could be attributed to the alternate influences of freezing–thawing interactions on texture (Reintam 1997). Therefore the distribution of particles could be attributed not only to pedogenesis but also to their physical separation (Mermut & St. Arnaud 1981). Moreover, some rare rusty neoferrans can be found at a depth of 20–30 cm (Fig. 2c). Oral conversation with Professor Karl Hartge indicates that some early frosts after several autumn moistening (Fig. 3) could also impact the subsoil compaction, making Hartge's (1994) "Lagerungskurve" positive.

Due to the development of both the humus-accumulative process and pedogenetic argillization during 40 years, the cation exchange capacity increased in the uppermost horizons to a depth of 20 cm, under a permanent plant cover even to a depth of 40 cm (Table 12). Formation of humus acids (first of all fulvic) has induced not only the appearance of hydrogen in the exchange complex but also an increase in actual acidity and a decrease in base saturation. At the same time, the amounts of exchangeable hydrogen as well as magnesium and potassium are highly variable among all variants (Table 13). Cation exchange capacity and the amounts of calcium are quite similar everywhere.

In spite of changes in the content of organic matter and silty-clayey particles, the specific surface area as one of the integral features of the soil status has remained in the limits of 31 ± 2 to 37 ± 2 m^2 g^{-1} during the whole period of 20 years. However, in the last two decades the specific surface area in the upper 5 cm increased to 53 ± 3 and in the next 5 cm to 43 ± 2 m^2 g^{-1}. This is in good correlation with the intensification of humus- and clay-accumulative processes as well as with the development of the soil profile on reddish-brown till.

Table 12. Cation exchange capacity after 40 years, $cmol_c$ kg^{-1}

Variant	Horizon and depth, cm	pH_{KCl}	CEC	Exchangeable cations					Base saturation, %
				Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	
I	A 0–5	6.83	16.0	12.0	2.3	0.6	0.1	1.0	93.8
	5–10	6.90	14.6	11.9	1.7	0.3	0.1	0.6	95.9
	Bw 10–20	7.15	15.1	12.7	1.2	0.2	0.1	0.9	94.0
	BC 20–30	7.12	13.8	12.1	1.1	0.1	0.1	0.4	97.1
	30–40	7.08	12.4	11.1	0.9	0.1	0.1	0.2	98.4
	40–50	7.16	11.8	10.3	0.9	0.1	0.1	0.4	96.6
	50–60	7.00	9.3	7.8	1.0	0.1	0.1	0.3	96.8
IV	A 0–5	7.05	14.5	11.5	1.7	0.4	0.1	0.8	94.5
	5–10	6.78	12.8	10.6	1.2	0.3	0.1	0.6	95.3
	Bw 10–20	7.00	13.0	11.7	0.8	0.2	0.1	0.2	98.5
	BC 20–30	7.41	11.6	10.6	0.6	0.1	0.1	0.2	98.3
	30–40	7.33	12.1	10.8	0.6	0.1	0.1	0.5	95.9
	40–50	7.03	12.2	11.2	0.6	0.1	0.1	0.2	98.4
	50–60	7.25	12.3	11.3	0.6	0.1	0.1	0.2	98.4
II	A 0–8	6.90	13.7	11.4	1.4	0.2	0.1	0.6	95.6
	Bw 8–20	7.12	14.0	12.6	0.9	0.1	0.1	0.3	97.9
	BC 20–30	7.05	12.8	11.3	0.8	0.1	0.1	0.5	96.1
	30–40	7.07	13.9	12.7	0.8	0.1	0.1	0.2	98.6
	40–50	6.99	12.9	11.6	0.9	0.1	0.1	0.2	98.5
	50–60	7.06	12.8	11.5	0.9	0.1	0.1	0.2	98.3
III	A 0–7	6.99	13.5	11.6	1.0	0.2	0.1	0.6	95.6
	Bw 7–20	7.17	12.6	11.4	0.8	0.1	0.1	0.2	98.4
	BC 20–30	7.27	13.2	12.0	0.8	0.1	0.1	0.2	98.5
	30–40	7.22	12.9	11.7	0.8	0.1	0.1	0.2	98.5
	40–50	7.17	12.8	11.5	0.8	0.1	0.1	0.3	97.7
	50–60	7.21	13.2	11.8	0.9	0.1	0.1	0.3	97.7

pH_{H2O} in all cases 7.0–7.9.

Table 13. Average exchange properties of all variants after 40 years, $cmol_c\ kg^{-1}$

Property	A-horizon		Bw-horizon		BC-horizon, 20–40 cm		BC-horizon, 40–60 cm	
	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %	$x \pm s_x$	V, %
CEC	14.2 ± 0.5	7.8	13.7 ± 0.6	8.2	12.9 ± 0.3	6.2	12.2 ± 0.4	10.1
Ca^{2+}	11.5 ± 0.1	4.3	12.1 ± 0.3	5.4	11.6 ± 0.3	6.8	10.9 ± 0.5	12.1
Mg^{2+}	1.6 ± 0.3	44.0	0.9 ± 0.2	36.9	0.8 ± 0.2	60.0	0.8 ± 0.1	50.0
K^+	0.3 ± 0.1	46.9	0.2 ± 0.0	38.3	0.1 ± 0.0	0.0	0.1 ± 0.0	0.0
Na^+	0.1 ± 0.0	0.0	0.1 ± 0.0	0.0	0.1 ± 0.0	0.0	0.1 ± 0.0	0.0
H^+	0.7 ± 0.1	24.7	0.4 ± 0.2	82.9	0.3 ± 0.05	47.1	0.3 ± 0.1	32.0
Base saturation, %	95.1 ± 0.3	0.9	97.2 ± 0.9	2.2	97.7 ± 0.4	1.2	97.8 ± 0.3	0.8

Morphology

During already the first decade, a thin (2.5–4.5 cm) weakly developed but diagnozable greyish A-horizon was formed under the sown perennial as well as under the annual vegetation. It was quite uneven under barley, forming only rare greyish spots where vegetation was absent and only some humus could accumulate from weed roots and microbes. Deeper than 20–25 cm traces of accumulated humus were lacking. Weak signs of pedogenetic argillization in situ and weathering of calcareous pebble and gravel were described in an unpublished MSc paper of Virve Olvi. She established that weak properties of a thin Calcaric Regosol had been developed. Further progress of pedogenesis during the second decade resulted in the formation of a well diagnozable A–Bw–(B)C profile in all variants (Fig. 2). An especially marked process had taken place under the spontaneous formation of the herbaceous cover after barley and lack of vegetation during the first decade. The depth of the A-horizon (10YR5/3) was already 5–(8)–10 cm; the weak Bw-horizon (5YR4/4) reached to a depth of 20 cm, in places even to a depth of 30 cm. At the same time, the increase in the humousness of some profiles per decade was smaller than the increase in depth (Reintam & Pogorelova 1986, 1987).

The development of the humus-accumulative, argillized in situ A–ABw–Bw–(B)C profile continued during the third and the fourth decade. After 30 years the A–ABw sequum was already 10–12 cm thick under the permanent grass-herbaceous sward (Fig. 2b) and only the variant with barley had a little thinner A-horizon (10YR5/4), poorer in humus. Cambi-argillic properties were evident to a depth of 20 cm but diagnostic to a depth of 40 cm. At the end of 40 years, the thickness of the well-developed A-horizon (10YR3/4) was about 10 cm in variants I and IV, characterized by a complete return of organic matter during 40 and 30 years, respectively (Fig. 2). The depth of 7–8 cm was described in the other two variants where elimination of aboveground phytomass had prevailed during the last decades. The cambi-argillic Bw-horizon (5YR5/6) occurred to a depth of 20 cm and was nutty-angular but relatively compact. Fine calcareous pebbles and gravel were found throughout the profiles. Reddish-brown calcareous till (5YR4/6) displayed signs of argillization in situ to a depth of 40 cm; deeper than 40 cm the till was non-compact. In 2004 the layer between 10 and 20(30) cm was dried up to discontinuous capillary moisture, which probably caused the compactness and a lighter value of chroma there (Fig. 2). Rare fine roots were found at a depth of 40–60 cm, and marked biological activity (fine roots, earthworms, humus traces) was noted to a depth of 40 cm as already during the third decade. The A–Bw–(B)C profile of Calcaric Regosol had developed, and the Calcaric Cambisol could be already diagnosed. The first signs of argilluviation (lessivage) were observable as well. The relationships between humus- and clay-accumulative phenomena, and pedogenic nonsiliceous iron were significant as suggested formerly (Kahle et al. 2002).

CONCLUSIONS

Perennial grass-herbaceous vegetation represents an excellent driving force for the development of humus-accumulative pedogenesis. During 40 years the net accumulation of organic carbon in the profile of 60 cm was ensured by almost equivalent amounts of humifiable above- and underground phytocoenotic agents in the conditions of not only the return of produced organic residues but also their partial removal from the site. In spite of the cyclic character of the mineralization and humification processes the latter prevail, and total annual increment of organic carbon in the formed and forming soil was observed. The removal of aboveground phytomass resulted in the significant impoverishment of the solum regarding nitrogen, total ash, and main nutrients. Therefore the humus-accumulative process and the

in-depth progress of the A–ABw sequence of the soil appear to be more intensive against the background of the permanent return of all residues.

The weathering of skeletal carbonates as well as of ferri- and alumosilicates, accompanied by the accumulation of amorphous sesquioxides and total pedogenic nonsiliceous iron, produces the products participating in the formation and fixation of R_2O_3-humic-fulvic complexes in neutral to slightly alkaline and base-saturated conditions. Primarily inhibited transformation of fulvates into humates has changed over time. During the third and fourth decades the process intensified, even while fulvic formations within the interlayeral structure of minerals diminished and probably transformed into more stable humic-fulvic complexes.

Against the background of argillization in situ, noted from the beginning of organic–mineral interactions in the studied reddish-brown till, a slight lessivage developed in the humus layer within a depth of about 10 cm. Nevertheless, at the end of the third decade a clay- and silt-accumulative profile was formed. Besides obvious humus-accumulative phenomena, synchronous weathering of sandy particles and formation and accumulation of silt and clay are also characteristic of pedogenesis on reddish-brown calcareous till during 40 years. Simultaneously, the increase in the cation exchange capacity and in the specific surface area progressed in the humus-enriched topsoil. A well recognizable Calcaric Cambisol (Rendollic Eutrochrept) profile with the horizon sequence A–ABw–Bw–BC–C had already developed from the Calcaric Regosol in the second and third decades.

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Mullateke punakaspruunil karbonaatsel moreenil rohttaimede all neljakümne aasta jooksul

Loit Reintam

Mullatekke ja tema arengu uurimiseks rohttaimede all rajati 1963. ja käivitati 1964. aastal Tartumaal Eerikal (58°22′ N, 26°36′ E) katse praktiliselt orgaanilise süsiniku ja lämmastiku vabal (vastavalt 0,6 ja 0,2 g kg^{-1}) punakaspruunil karbonaatsel moreenil. Kolme eelmise aastakümne tulemused on varem avaldatud. Siinne kirjutis käsitleb sünkroonseid produktsiooni- ja mullatekkeprotsesse neljandal aastakümnel, aga ka kogu nelikümmend aastat kestnud katse jooksul. Igasugusele mullatekkele omane hoogne, olemuselt laineline ja tsükliline huumus-akumulatiivne protsess (kamardumine) on jätkunud pidevalt. Seda on saatnud korese karbonaatide lagunemine ning osaline leostumine, amorfsete ning kristalliseerunud murenemissaaduste moodustumine ja kogunemine, koha peal savistumine ning huumusest rikastunud õhukese mulla ülakihis peene tolmu ja ibe nõrk lessiveerumine. Orgaanilise süsiniku ja lämmastiku jätkuva kogunemise tagas ekvivalentne kogus produktsiooniprotsessi humifitseerumisvõimelisi saadusi. Et viimaste moodustumine oli ajaliselt dünaamiline, oli ajaline perioodilisus iseloomulik ka mineralisatsiooni ja humifikatsiooni vahekordadele sünkroonses mullatekkes. Väike C : N suhe näitab esmase mullatekke algusest peale moodustunud huumuse suurepärast kvaliteeti. Juba kolmanda aastakümne lõpuks selgus, et huumuse kümmeaastakuti dünaamilise fulvaatsuse ja üldise lahustuvuse vähenemise taustal toimus Ca-humaatide muundumine humiinideks ning R_2O_3-humaat-fulvaatsete komplekside teke RO-humaat-fulvaatsetest moodustistest. Humaat-fulvaatsete komplekside sidemed inaktiivsete poolteisthapendite ning savimineraalidega tugevnesid ja fulvohapete kogus savimineraalide struktuuris vähenes neljandal aastakümnel. Liivafraktsioonide murenemisel moodustusid ja kogunesid tolmu- ning ibeosakesed. Seetõttu suurenesid tekkinud muldades osakeste eripind ja katioonide neelamismahutavus. Neljakümne aasta jooksul arenes punakaspruunile karbonaatsele moreenile väga nõrgalt leostunud pruunmulla (Calcaric Cambisol, *WRB*; Rendollic Eutrochrept, *US Soil Taxonomy*) A–Bw–BC profiil.