

Rates of soil-forming processes in three main models of pedogenesis

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ABSTRACT

Rates of soil-forming processes were evaluated for the three major models of pedogenesis: (1) normal "top-down" soil development (pedogenesis transforms the parent material under a geomorphically stable surface), (2) soil development accompanied by pedoturbation (turbational model), and (3) soil development accompanied by or alternating with sediment deposition on the soil surface (sedimentational model). According to the normal model, the rates of pedogenic processes exponentially decrease with time, so that in 2–3 ka after the beginning of pedogenesis, temporal changes in the soil properties become negligibly small, which is typical of soils in the steady state. Under humid climate conditions, the rates of many processes (accumulation and mineralization of humus, leaching of bases, migration of sesquioxides, textural differentiation, and so forth) are much higher than under arid climate conditions. For example, the rate of textural differentiation in soils of humid climates is one to two orders of magnitude higher than that in soils of arid climates, and the rate of humus accumulation and rejuvenation is several times higher. The rate of the zoogenic turbation of soil material with the input of fine earth onto the soil surface and gradual burial of archaeological artifacts into the soil is maximal in Chernozems, where it is two times higher than in Kastanozems and gray forest soils (Humic Luvisols) and five times higher than that in Albeluvisols and Podzols. For soils developing according to the sedimentation model, the degree of development of the soil profile depends on the rate of sedimentation on the soil surface. Thus, with high rates of alluviation (>2.5 mm/yr), pedogenetic processes cannot significantly transform the alluvium. At the moderate rate of alluviation (0.3–1.0 mm/yr), typical aggradational soils –Fluvisols– are formed; the alluvial stratification is well seen in their profiles. At the low rate of alluviation (<0.1 mm/yr) and a considerable duration (>1000 yr) of pedogenesis, floodplain soils have relatively similar properties as the corresponding zonal soils (Luvisols, Chernozems).

Keywords: soil genesis, soil evolution, rate of soil-forming processes, Pozols, Luvisols, Chernozems.

RESUMEN

Se evaluaron los tiempos característicos de formación de suelo siguiendo los tres modelos principales de pedogénesis: (1) desarrollo "normal" del suelo de la superficie hacia la profundidad (la pedogénesis transforma el material parental en sitios estables en términos geomorfológicos), (2) desarrollo de suelo acompañado de pedoturbación (modelo turbacional), y (3) desarrollo del suelo acompañado por o alternando con depositación de sedimentos en la superficie del suelo (modelo sedimentacional). De acuerdo con el modelo normal de pedogénesis, las tasas de los procesos pedogenéticos decrecen exponencialmente con el tiempo, de tal forma que después de 2 a 3 ka después del inicio de la formación del suelo los cambios en las propiedades del suelo en el tiempo se vuelven insignificamente pequeños,

lo cual típicamente corresponde a suelos que se encuentran en un estado de equilibrio aparente. Bajo condiciones climáticas húmedas, las tasas de varios procesos (acumulación y mineralización de la materia orgánica humificada, lixiviación de bases, migración de sesquióxidos, diferenciación textural, etc.) son mucho mayores que bajo condiciones climáticas áridas. Por ejemplo, la tasa de diferenciación textural en suelos formados bajo condiciones húmedas es entre una y dos órdenes de magnitud mayor que en suelos formados en climas áridos, y la tasa de acumulación de materia orgánica humificada y el rejuvenecimiento es también varias veces mayor. La tasa de turbación por actividad animal en conjunto con la depositación de sedimento fino en la superficie del suelo y el enterramiento gradual de artefactos arqueológicos en el suelo es máxima en Chernozems, donde es dos veces mayor que en Kastanozems y en Luvisoles húmicos y cinco veces mayor que en Albeluvisoles y Podzoles. Para suelos que se desarrollan de acuerdo al modelo sedimentacional, el grado de desarrollo del perfil de suelo depende de la tasa de depositación de sedimento en la superficie del suelo. Bajo tasas altas de depositación aluvial (>2.5 mm/a), los procesos pedogenéticos no pueden transformar en forma significativa al material aluvial. Bajo tasas moderadas de depositación aluvial (0.3–1.0 mm/a) se forman suelos agradacionales típicos –Fluvisoles–, en cuyos perfiles es evidente la estratificación aluvial. A una baja tasa de depositación de material aluvial (<0.1 mm/a) y después de periodos largos de pedogénesis (>1000 a), los suelos de las planicies fluviales tienen propiedades similares a los suelos zonales (Luvisoles y Chernozems).

Palabras clave: génesis de suelos, Podzoles, Luvisoles, Chernozems.

INTRODUCTION

At present, we have insufficient and often ambiguous data on the rates and characteristic times for the development of soils and the particular processes of soil formation. Soil studies on dated surfaces (the method of soil chronosequences) showed that the development of mature soils requires thousands of years; normally, from 1,500 to 7,000 years (Crocker and Major, 1955; Duchaufour, 1968, 1970; Stevens and Walker, 1970). Other authors suggest that soil development proceeds much more slowly, so that only primitive soils are formed in the Holocene in arid regions (Bockheim, 1980; McFadden *et al.*, 1986; Nettleton *et al.*, 1989; Reheis *et al.*, 1992). A contrary view is that a number of soils can be formed within a relatively short time and can be almost fully shaped within less than 100 years (Tolchel'nikov, 1986).

The method of chronosequences was applied to study the rates of pedogenetic processes on different objects, including mountain moraines and sandy bars of different ages on the shores of lakes and seas (Stevens and Walker, 1970; Gennadiev, 1978; Kuznetzova, 2000). In the areas of loess deposition and mantle loams, buried paleosols of different ages have been studied (Zolotun, 1974; Alexandrovskiy, 1983; Ivanov, 1992; Demkin, 1997). The Holocene chronosequences of surface soils developed from loamy substrates were studied in several areas around the world (Stevens and Walker, 1970; Gennadiev, 1990; Birkeland, 1999; Lisetskii, 2000). It should be noted that these soils are widespread throughout the world, and their evolution is much more complicated than that of sandy soils and soils developed from resistant bedrock.

The use of the radiocarbon method makes it possible not only to obtain the dates of particular soils in soil chronosequences but also to determine the rate of organic carbon

exchange in the studied soils (Scharpenseel, 1971). Various indices have been suggested to judge the degree of development of particular soils, soil horizons, and the particular soil features (Harden, 1982; Birkeland, 1999).

MATERIALS AND METHODS

The studies were performed within the Russian Plain. Soil chronosequences of different origins have been studied, including (1) the development of sandy Podzols on the rising coasts of the Baltic Sea and Lakes Ladoga and Onega, and (2) the development of loamy Chernozems and Luvisols on artificial dumps, burial mounds, and artificial levees with ages from 10 to 5,000 years. 3) Soil development along the sedimentation model was studied by the example of chronosequences of buried and surface soils in the bottoms of gullies and on floodplains. (4) Soil development in the turbational model was studied with the help of archaeological markers (artifacts) of different ages found in the profiles of Chernozems and Luvisols in the forest steppe zone. In this work, the results of these investigations are compared with some data of other researchers obtained in different regions of the world.

To gain reliable results, it is necessary to study soil chronosequences developing from the same parent material under stable bioclimatic conditions during the whole period covered by a given chronosequence (Jenny, 1941; Stevens and Walker, 1970; Gennadiev, 1990; Birkeland, 1999). It is known that not only within the zone of glaciation but also further south of it (approximately to the latitude of 40° N), climatic and biotic conditions for a very long period (more than 70 ka) before the Holocene were different from those in the Holocene (*i.e.*, within the last 10–12 ka), and that pedogenic processes in the pre-Holocene period were

either interrupted or proceeded in a different direction than those in the Holocene. The duration of interglacial stages was shorter than the duration of glacial stages. Therefore, the analysis of very long chronosequences results in the underestimation of the rates of pedogenic processes that assume Holocene climatic conditions.

Therefore, Holocene chronosequences are used in this study. The objects selected for study show the development of humus, carbonate, argillic, and other horizons under relatively stable environmental conditions within a period ranging from a hundred years to 10,000 years. For definition of soil age, the data of archeology, history, and radiocarbon dating are used.

RESULTS

Normal “top down” model of pedogenesis

Sandy Podzols

The analysis of results from several chronosequences of Podzols in Eastern Europe, along with data obtained by other researchers (Crocker and Major, 1955; Plichta, 1970; Stevens and Walker, 1970; Jauhiainen, 1973; Huggett, 1998; Birkeland, 1999), makes it possible to estimate the rates of development of soil horizons. The data are summarized in Table 1. In the Baltic region, sandy Podzols pass through a short-term stage with an A-C profile during the first decades of development. Subsequently, in Podzols developing from iron-depleted quartz sands, the bleached eluvial horizon appears. The formation of the iron-illuvial Bf horizon (Bs horizon in the WRB classification), which usually has a greater thickness than the E horizon, requires longer periods, because significant amounts of Fe₂O₃ have to be accumulated. On polymictic sands enriched in iron, the Bs horizon manifests itself earlier than the E horizon, because the accumulation of pedogenic iron compounds takes place throughout the entire profile, and the podzolization of the A1 and E horizon is masked by humic substances.

In general, considering available data on the development of Podzols, it is possible to distinguish between two different regions. In the northern region, encompassing taiga

areas with shallow Podzols (Karelia and Finland), the self-development of Podzols proceeds in the following stages: (a) a short stage (up to 300 years) of the downward growth of the soil profile and (b) a longer stage of its differentiation (300–2,000 years). To the south, in the Baltic region, the differentiation of the soil profile proceeds in parallel with its downward growth. After 300 years of soil development, the thickness of soil horizons, as well as the degree of the soil profile differentiation, continues to increase with time. Then, a quasi-equilibrium stage (steady state condition) takes place, during which changes in the thickness of soil horizons and their morphological manifestation are relatively minimal and within the limits of the natural spatial heterogeneity of the soil cover. However, gradual changes in some of the soil properties may be observed during this stage.

Analysis of the literature shows that these distinctions in the development of Podzols have a zonal nature. The first (northern) region includes the areas with shallow Podzols (the thickness of their eluvial layer is less than 10 cm), whereas the southern region is the area of deeper soils (the thickness of the eluvial layer is 15–30 cm) (Aaltonen, 1939; Crocker and Major, 1955; Duchaufour, 1968, 1970; Plichta, 1970; Stevens and Walker, 1970; Jauhiainen, 1973; Alexandrovskiy, 1983; Birkeland, 1999; Kuznetsova, 2000).

In the humid tropical and subtropical regions, the increase in the thickness of sandy podzolic soils does not stop at the soil age of 1,500–2,000 years; this process has been active during the entire Holocene, and its rate has been much higher than in the temperate zone. As a result, in 2,100 years after the beginning of the soil formation, the thickness of the eluvial and illuvial horizons reaches 45 and 65 cm, respectively; after 4,200 years, it is about 65 cm for the eluvial horizon and more than 130 cm for the illuvial horizon (Burgess and Drover, 1953). On sandy surfaces of Pleistocene age, the thickness of the eluvial layer may reach several meters (Thompson, 1981). Under this uniquely deep eluvial layer, a relatively thin Bs horizon is found. The thickness of the Bs horizon in such Podzols appears to decrease with time, which may be related to the leaching of sesquioxides (particularly, iron) beyond the soil profile.

Luvisols

Published data on soil chronosequences developing from loamy substrates include studies reported in Duchaufour (1970), Stevens and Walker (1970), and Birkeland (1999). According to these data, the development of Luvisols on non-calcareous parent material proceeds through the following stages: 1) 0–10 (and up to 15) years, a profile with O-C or AO-C horizons with a thickness of several centimeters is formed. 2) 30–50 years, the profile with O-AO-A1-A1C-(Bw)-C horizons with a total thickness of up to 15 cm is formed. 3) 70–140 years, further differentiation of the profile results in O(AO)-A1(A1E)-Bwt(Bt)-C horizons with the solum thickness reaching 25 cm; the

Table 1. Rates of increase in the thickness of humus horizons of sandy Podzols in the Baltic region during different stages of soil development (in cm/100 yr).

Horizons	Time (years)			
	First hundreds	Hundreds	First thousands	Thousands (mature stage)
Eluvial part of the profile (A+E)	<u>0–4</u> 1	<u>0–1.5</u> 0.5	<u>0–0.8</u> 0.2	0
Full solum (A1+E+B)	<u>0–25</u> 10	<u>0–5</u> 2	<u>0–1.5</u> 0.5	<u>0–0.4</u> 0.1

Underlined values: lower and upper limits; bold values: average rates.

illuvial horizon is often formed before the eluvial horizon. 4) 150–500 years, the thickness of the eluvial layer (A1 + E) reaches 10–15 cm, and the thickness of the Bt horizon is 30–50 cm. 5) 800–1,000 years, well-differentiated soil profiles with O(AO)-EA1-EB-Bt-Bca horizons are formed; the thickness of E horizons is up to 20 cm, and the thickness of Bt horizons is up to 70 cm. In the soils developed from loess and mantle loams, the rate of textural differentiation is much higher than that in the soils developed from moraine deposits. On land surfaces with an age of 1,500–2,000 years, the development of Luvisol profiles continues and the thickness of their horizons approaches that in the Holocene soils. Luvisols on the surfaces of 2,500–3,000 years are very similar to soils that developed throughout the Holocene (Table 2). The rate of humus accumulation in Luvisols with an age of 500 years decreases by 10–35 times (in comparison with the initial period of their development). Then, in Luvisols with a mature profile, the rate of humus accumulation is equal to zero (as the input and mineralization of humic substances are in equilibrium). At the same time, the rate of lessivage within the first 3,000 years of the development of Luvisols remains virtually stable. Then, at the quasi-equilibrium stage, when the thickness of the soil horizons becomes stabilized, the rate of lessivage decreases considerably (by approximately three times).

At the same time, there are known cases of long-term and slow development of Luvisols. The study of long soil chronosequences on gravelly deposits of river terraces in subtropical climate conditions (in Slovenia) demonstrated gradual weathering of coarse sediments and their transformation into clayey substrates (Vidic, 1998). Under these conditions, the Bt horizons appear in the soil profiles in tens or hundreds of thousand years after the beginning of pedogenesis.

Chernozems

On the Russian plain, in 15 years after the beginning of soil formation, the thickness of the profile (A + AB horizons) constitutes 7 cm; in 100 years, 18 cm; in 800 years, 45 cm; and in 2,000–4,000 years, 80–90 cm. The rate of the increase in soil profile thickness depends on the stage of soil development: during the first 20 years, it reaches 4–5 mm/year; in 100 years, it decreases to about 1.5 mm/year on average (1.3 mm/year in a period from 20 to 100 years); in 800 years, to 0.6 mm/year on average (or about 0.4 mm/year in the last centuries); in about 3,000 years, the average rate is 0.3–0.4 mm/year (0.2–0.25 mm/year in the interval from 800 to 3,000 years after beginning of soil formation). Then (from 3,000 to 10,000 years after beginning of soil formation), the rate of increase in the Chernozems thickness becomes less than 0.05 mm/year. Similar rates of soil development were reported for prairie soils in North America: 33 cm during the first 400 years. Subsequently, the rate of pedogenesis decreases to less than 0.05 mm/year (Stevens and Walker, 1970; Buol *et al.*, 1973). In the Kuban region (North Caucasus), the rate of Chernozem development is higher: the average increase in soil thickness for a period of 3,000 years reaches 0.5 mm/year. These values are important in the context of establishing permissible rates of erosion: for steppe soils, the permissible rate of soil erosion should be less than 0.25 mm/year or 2.75 t/ha per year, assuming that adequate parent material exists that can be transformed to soil.

The rates of leaching of carbonates with development of Chernozems are comparable with the rates of growth of the humus profile, with the maximal values during the first stages of soil development. The average rate of leaching of carbonates in 300 years reaches 1 mm/year, and in 2,500

Table 2. Changes in soil properties and rates of soil-forming processes in the sequence of Luvisols in cis-Carpathian regions.

Age (years)	10	35	100	500	1,000	2,000	3,000	10,000
Profile thickness (A+B) (cm)			5–10	50–70	85	>100	150	>160
Thickness of eluvial horizons (cm)			5	16–20	20	30–35		30–40
Bulk density in the B horizon (g/cm ³)			0.9–1.0		1.1–1.3	1.35–1.55		
pH _(water) in the eluvial horizon		5.2–7.3	4.0–6.7		3.8–6.2	4.3–5.5		4.5–5.5
Humus accumulation (g/m ² per year)	<u>7</u> 0.7		<u>70</u> 0.7*	<u>90–100</u> 0.02–0.06		<u>100</u> 0		<u>~100</u> 0
Lessivage (g/m ² per year)		<u>40</u> 1.2		<u>200–300</u> 0.5	<u>500–1,000</u> 0.5–1	<u>1,000–2,400</u> 0.5–1		<u>2,000–2,500</u> 0.25
Leaching of CaCO ₃ (g/m ² per year)		<u>30</u> 0.8		<u>700–1,000</u> 0.85				

Underlined values: mass of accumulated or removed substances in t/ha; bold values: the rate of substance accumulation or removal in t/ha per year. * The rate of soil processes was calculated with respect to the previous member of the chronosequence, e.g., 70–7 = 63 g/m², 100–10 = 90 years; hence, 63/90=0.7.

years drops to 0.15 mm/year. Upon irrigation, the leaching of carbonates is accelerated up to 140 g/m² per year (during 46 years of irrigation) (Ivanov, 1989). This change in the content of carbonates is related to the drastic change in the water regime of the studied soils after the beginning of irrigation.

Sedimentation model

Typical floodplain soils –Luvisols– are formed under conditions of regular alluviation ensuring the upward growth of the soils; these are cumulative soils (Ferring, 1992). On more ancient parts of floodplains, Chernozems, Luvisols, and other soils typical of terraces and interfluvies can be found (Alexandrovskiy *et al.*, 2004a). The rates of pedogenic processes have been determined for recent, archaeologically and historically dated soils and sediments, as

well as for ¹⁴C-dated paleosols on the floodplains (Table 3) (Alexandrovskii, 2004; Alexandrovskiy *et al.*, 2004b).

On the basis of more than 40 radiocarbon dates, the following intervals of soil formation in the floodplains of the Oka and Moskva Rivers were established: I: 0–300 BP; IIa: 800–2,000 BP; IIb: 2,200–3,000 BP; III: 3,200–4,200 BP; IV: 4,700–6,000 BP; V: 6,300–7,800 BP; VI: 8,200–10,000 BP; and VII: 11,000–12,500 BP. The main stages of soil buried under alluvial sediments were confined to the following periods: 300–800; 4,200–4,700; 7,800–8,200; and 10,000–11,000 BP; they corresponded to the phases of climatic cooling.

Turbational model

A significant role in the development of Chernozems and other soils of the steppe and forest steppe regions belong

Table 3. Radiocarbon ages of buried and surface floodplain soils.

Soil no.	Soil	Dated material	Horizon	Depth (cm)	Code	Date (BP)
<i>Middle Oka River, Nikitino-Klimenty section</i>						
I	Modern Fluvisol	cc	C	50	IGAN-XX	320±90
II*	Grey Wooded soil (Luvisol)	ha	A1	136-143	IGAN-1212	1,500±90
II**	Grey Wooded soil (Luvisol)	ha	A1E1	165-186	IGAN-1211	2,280±110
III	Fluvisol	ha	A1	260-280	IGAN-1210	3,780±90
IV*	Phaeozem (upper part)	ha	A1	420-430	IGAN-1209	4,880±120
IV**	Phaeozem (lower part)	ha	A1	435-455	IGAN-2323	5,910±260
<i>Moskva River, Khimka-1 section</i>						
II-III	Luvisol	ha	AE	120-127	IGAN-2321	1,780±80
IV-VI	Luvisol	ha	AE	176-183	IGAN-2320	5,460±160
VII	Cryosol, Allerod	ha	A1	205-210	IGAN-2319	11,780±290
		ha	A1	205-210	Ki-10562	11,260±300
<i>Brateevo section</i>						
VI	Phaeozem	ha	A1	260	IGAN-2550	8,760±310
<i>Myakinino section</i>						
II	Fluvisol (upper part)	cc	A1 ₁	220	Ki-10524	1,220±70
<i>Kur'yanovo section</i>						
II-III	Fluvisol (lower part)	ha	A1	130-165	IGAN-2083	2,850±70
	Alluvium	cc		200	Ki-10522	5,305±90
V	Fluvisol	ha	A1g	280	IGAN-2648	7,010±150
<i>Terekhovo section</i>						
II-IV	Luvisol	ha	AE	160-170	IGAN-2549	2,430±180
<i>Stavropol territory, Kalaus River, Ipatovo section</i>						
	Fluvisol	ha	A1	30-50	IGAN-2363	660±70
	Fluvisol	ha	A1	150-175	IGAN-2362	1,800±50
	Fluvisol	ha	A1z	250-300	IGAN-2360	2,860±70
<i>Chla section</i>						
	Solonetz soil	ha	AB	215-245	IGAN-2361	1,890±40
	Chernozem	ha	A1z	340-370	IGAN-2359	6,200±90
	Fluvisol	ha	A1z	530-560	IGAN-2358	8,370±110

ha: humic acids; cc: charcoal.

to zoogenic turbation. Soil fauna (earthworms, earth-burrowing rodents, etc.) dig out onto the soil surface considerable masses of fine earth; a layer with a thickness of up to 3 mm/year is formed on the surface owing to their activity (Darwin, 1882; Hole, 1961; Dmitriev, 1988). Gradually, a biomantle of the fine earth transferred by the animals onto the soil surface is formed (Johnson, 1990).

In an experiment in the Tula region, a thin layer of gravel was put onto the surface of the gray forest soil (Luvisol); in four years, it was partially buried under earthworm coprolites; in seven years, it was buried under a 1.5–2.0 cm layer of coprolites. More ancient archaeological artifacts are buried to a greater depth: 10 cm (180 years), 15 cm (450 years), 20–25 cm (1,000 years), 25–35 cm (2,400 years), 30–50 cm (5,000 years). Mesolithic artifacts dating back to the beginning of the Holocene are buried to a depth of 70–100 cm in Chernozems and 35–60 cm in the gray forest soils (Luvisols) of western Ukraine (Alexandrovskiy and Matskevoi, 1989).

This effect is caused by the directed action of zoogenic turbation. The fine earth transferred by the animals onto the soil surface is involved in pedogenesis and serves as the source of material increasing the thickness of the humus horizon. The intensity of zoogenic turbation depends on the biomass production and is positively correlated with the humus (A) horizon thickness. This continuous process gradually attenuates with time and leads to the burial of surface soil horizons, archaeological artifacts, and coarse rock fragments in the fine earth thickness. Table 4 contains data on the average rate of burying of the artifacts and increase in the depth of burying for different time spans. These data suggest that both values tend to decrease in the course of time.

DISCUSSION

In order to understand the development of soil systems in time, one should know temporal parameters of this development, such as (a) the duration (age) of pedogenesis that is controlled by the age of the surface and, hence, has a geomorphic nature, and (b) the rates of soil-forming processes and their characteristic times to produce soil morphologic features. It is important that these parameters of soil development are fundamentally different for the main models of

pedogenesis considered in this study: normal, denudational, aggradational (sedimentational) (Targulian, 1982), and turbational (Alexandrovskiy, 2003). In reality, many soils develop according to several models that act simultaneously. For example, the development of floodplain soils can be described within the framework of a combination of sedimentational, normal, and zooturbational models.

The available data on rates of soil processes are mainly appropriate for estimating the normal model of pedogenesis and characterize the development of particular horizons or the entire soil profiles. The materials obtained in western and eastern Europe and in Alaska suggest relatively rapid rates of soil development (Crocker and Major, 1955; Duchaufour, 1970; Plichta, 1970; Gennadiev, 1990; Ivanov, 1992) in comparison with those reported for the regions with drier climate (Harden, 1982; McFadden *et al.*, 1986; Reheis *et al.*, 1992; Birkeland, 1999).

Normal “top down” model of soil development

This model suggests that soil development proceeds downward into a sediment under conditions of a stable soil surface (in the absence of major erosion, sedimentation, or bioturbation). Characteristic times of the particular stages of this development are different for different types of soils. For example, sandy Podzols acquire the initial differentiation (E-Bs) in about 50–100 years and reach the equilibrium state in 1500 years. These times for Albeluvisols (Soddy-podzolic loamy soils) (E-Bt) are 100–500 and 2,500–3,000 years, respectively; for Luvisols (gray forest soils) (A1E-Bt), 300–700 and 3,000 years; for Chernozems (A1-Bk), 100–200 to 2,500–3,000 years; for Kastanozems (A-Bk-Bz), 100–200 and 1500–2000 years; and for Solonchets (E-Bt-Bk-Bz), 100–200 and 1,000–2,000 years, respectively (Table 5).

The study of soil chronosequences demonstrates an important feature of pedogenesis, namely that there are regular changes in the rates of particular soil processes in the course of soil development from the initial stage to the mature stage within a period of up to 2,000 years. The soils of different ages and different degrees of development provide important information that allows us to judge rates of soil genesis, the age of land surface in which the soil is developed, and the effects of possible additional sediment input (*i.e.*, to determine if normal or sedimentational models

Table 4. The rates of burying of the artifacts into the soil thickness under the impact of zooturbation (mm/year).

Soil	Zoogenic burying	Time interval (years)					
		0–10	10–100	100–1,000	1,000–2,500	2,500–5,000	5,000–10,000
Gray forest	Average rate	2	0.7	0.22	0.12	0.08	0.05
	Increment	–	0.56	0.16	0.053	0.04	0.02
Chernozem	Average rate	3.5	1.2	0.35	0.2	0.13	0.085
	Increment	–	0.94	0.26	0.1	0.068	0.036

Table 5. Characteristic times of soil development.

Soil	Characteristic time of stages (years)		
	Development of the profile A-C	Appearance of diagnostic horizons	Mature profile
Tundra Gleysols A-G	10	10–20	200
Sandy Podzols E-Bs	20	50–100	1,500
Loamy Sod-Podzolic E-Bt	10	100–500	2,500–3,000
Gray forest A1E-Bt	5–10	300–700	3,000
Chernozems A1-Bk	5	100–200	2,500–3,000
Kastanozems A-Bk-Bz	10	100–200	1,500–2,000
Solonetz E1-Bt-Bk-Bz	10	100–200	1,000–2,000

of pedogenesis are applicable). This information can be quantitatively estimated for the soils with an age of up to 2–3 ka. After this time, rates of soil processes decelerate, and the exact determination of their rates poses a serious challenge for researchers. To obtain quantitative estimates, it is also necessary to analyze such soil chronosequences in which all other factors of soil development (relief, parent material, climate, and biota) are similar. For floodplain soils developing according to the sedimentational model (see below), the stability of rates of pedogenic processes allows us to determine the duration of the stages of pedogenesis and alluviation and to determine the intensity of the latter. Note that temporal trends in the development of soil processes are recorded in the soil profile, which makes it possible to reconstruct them.

Sedimentation model of soil development

This model is studied by the examples of floodplain soils. The stratigraphy, genesis, and age of paleosols buried in floodplain sediments of the Moskva River and other rivers of the Russian Plain attest to the fact that the genetic profiles of floodplain soils depends on the rate of alluviation. If the rate of alluviation exceeds 25 cm/100 years, soil-forming processes do not have enough time to significantly transform alluvial sediments. At the rate of 10–25 cm/100 years, alluvial layers bear evident features of pedogenetic transformation (Table 6). At the rate of 1–3 cm/100 years, aggraded (stratified Luvisols) soils are formed; at the rate of 3–10 cm/100 years, well-developed Fluvisols (Soddy and Soddy Meadow alluvial soils) are formed. Normal (zonal) soils (Luvisols, Chernozemic, and others) are formed if the rate of alluviation is less than 1 cm/100 years. The following stages of soil development can be distinguished on the floodplains in the center of the Russian Plain: 1) initial soil with a weakly developed A1 horizon has a characteristic time of formation of about 100–200 years; 2) specific floodplain soils (Fluvisols) are formed in 300–1000 years, provided that the alluviation is absent or has a low rate (1–3 cm/100 years); 3) the development of zonal soils takes place if the rate of alluviation does not exceed 1 cm/100 years and re-

quires a period of about 1000 years. Knowledge of the rates and characteristic times of pedogenetic processes makes it possible to determine the soil age (both for floodplains and interfluves) and the rate of alluviation (for floodplains) from the degree of development of particular genetic soil features. The presence of buried soils in the alluvium attests to interruptions in the alluviation process.

Turbational model of soil development

This model is vividly manifested in many steppe and forest steppe soils. Two groups of pedoturbation can be distinguished: chaotic pedoturbation and pedoturbation directed towards the soil surface. Chaotic pedoturbation ensures the development of isotropy in the soil profile. In this study are results from the second group of pedoturbation producing the anisotropy in the soil profile (*sensu* Hole, 1961). Every year, earthworms and earth burrowing rodents transfer significant amounts of soil fine earth from deep soil horizons onto the soil surface, which leads to a gradual burial of ancient soil surfaces and various artifacts into the soil body. The amount of fine earth transferred by soil animals onto the soil surface may reach 22 mm/year and more (Darwin, 1881). In an experiment, coarse fragments placed on the soil surface were buried under the coprogenic material to a depth of 1.5–2.0 cm in seven years. More ancient archaeological tracers may be buried to a more considerable depth: 10 cm in 180 years, 15 cm in 450 years, 20–25 cm in 1,000 years, 25–35 cm in 2,400 years, and 30–50 cm in 5,000 years (Alexandrovsky, 2003). Mesolithic artifacts dating back to the beginning of the Holocene are found at a depth of 70–100 cm in Chernozems and 35–40 cm in gray forest soils. Thus, coarse soil particles, stones, and archaeological artifacts gradually sink down the soil profile towards the lower boundary of the thickness subjected to soil zooturbation. The characteristic time of this process is assessed at 5,000–10,000 years. The fine earth material extracted by zooturbation onto the soil surface is involved in pedogenetic processes and serves as a source of additional material for the humus horizon; the thickness of the humus horizon increases.

Table 6. Influence of the rate of alluviation on the development of cultural layers (habitation deposits) on floodplains.

Rate of sedimentation	Time required for soil formation (characteristic time of pedogenesis)	Soils and sediments	Archaeology
>25 cm/100 yr		Alluvium	Occasional findings (artifacts)
10–25 cm/100 yr		Sediments with pedogenetic features	Occasional findings (artifacts)
3–10 cm/100 yr	50–300 years	Cumulative (syn-sedimentational soils: soddy stratified, Fluvisols)	Cultural layers of short-term (seasonal) settlements
1–3 cm/100 yr	300–1000 years	Well-developed Fluvisols	Cultural layers of long-term (decades and centuries) permanent settlements
<1 cm/100 yr	> 1000 years	Normal (zonal) soils: Luvisols, Chernozems, Kastanozems	

Soil processes—humus accumulation, aggregation, and leaching of carbonates—proceed somewhat faster than the accumulation of the material extracted through zooturbation onto the surface of Chernozems. The same process is typical of Luvisols, but the rate of accumulation of the fine earth material extracted by animals onto the soil surface is relatively lower. Zoogenic pedoturbation in Luvisols does not prevent the development of mature eluvial and illuvial horizons. The soil profile tends to develop upwards following the gradually aggrading soil surface. In the course of time, the lower part of the A1 horizon in Luvisols is transformed into the upper part of the E horizon. The lower part of the E horizon becomes the zone of clay illuviation, *i.e.*, it transforms into the Bt horizon. Thus, it can be supposed that in the case of the absence of zoogenic pedoturbation with the accumulation of the fine earth material extracted from the lower horizons on the soil surface, Chernozems would have a smaller thickness, whereas the profile of Luvisols would display a more pronounced differentiation into the E and Bt horizons.

The intensity of zoogenic pedoturbation depends on the net primary productivity; in Chernozems, it is positively correlated with the thickness of the humus (A, A+AB) horizon. The effect of continuous and discontinuous zooturbation can be traced in the pollen, archaeological, radiocarbon, and other temporal markers in soils. The zooturbation process can sometimes be distinguished from slope, alluvial, and eolian processes by its more continuous spatial distribution and more or less even rates across vast regions, especially if considerable time spans (centuries and millennia) are analyzed.

CONCLUSIONS

The character and rate of pedogenetic processes have been analyzed with three models of pedogenesis: normal, sedimentational, and turbational pedogenesis. Normal pedogenesis is characterized by the evenness of the rates of pedogenetic processes during the particular stages of pedogenesis from time zero to the establishment of dy-

namic equilibrium with the environment (a mature stage). Sedimentational pedogenesis is characterized by the unevenness in the rates of pedogenetic processes. Formation of well-developed soil profiles, including Luvisol profiles, on floodplains attests to the existence of long periods without the accumulation of alluvial sediments on the soil surface. During these periods, soil profiles develop and approach a state of dynamic equilibrium.

The development of pedogenic processes in the normal model (the generally downward development of the profile on a stable soil surface) is also characterized by a gradual decrease in the rates of pedogenic processes with time. In the temperate zone, the development of soil profiles attenuates considerably by about 1,500 years for Podzols and by 2,000–3,000 years for Luvisols and Chernozems. Then, a stage of dynamic equilibrium may be approached. Many different sources of data indicate that the main soil profile-forming processes (humus accumulation, migration of iron and aluminum compounds, lessivage, and so on) are most active during the first decades or centuries of soil development, when the soil profile is still far from an equilibrium state.

In general, in humid climates of eastern Europe and in fact across much of the temperate zone, rates of pedogenic processes are rather high (Duchaufour, 1970; Gennadiev, 1978). They are much higher than the rates of pedogenic processes obtained in arid regions on the basis of studying long soil chronosequences (Harden, 1982; Birkeland, 1999). For example, the rates of accumulation and rejuvenation of humus in soils of humid areas are several times higher than those in soils of arid areas; the difference in the rates of textural differentiation is up to two orders of magnitude greater. The rate of zoogenic turbation of soil material with the input of fine earth onto the soil surface and gradual burial (submersion) of archaeological artifacts into the soil is maximal in Chernozems (in these soils, it is two times higher than that in Humic Luvisols and Kastanozems and five times higher than that in Albeluvisols and Podzols).

The pattern of soil development in the turbational and sedimentational models is dictated by the intensity of non-soil exogenous (biologic and geomorphic) processes. In the

turbational model, this is the transfer of fine earth onto the soil surface by burrowing animals and earthworms resulting in the gradual burial of coarse rock fragments and various artifacts into the soil. As well as in the normal model, this process gradually attenuates with time, which is seen for the soil with deep humus horizons.

The rate of sedimentation processes on floodplains and slopes (slopes are not much discussed in this paper until now) is very uneven in space and time. However, owing to the much more regular rates of pedogenic processes (characteristic rates of soil processes) depending on the particular environmental conditions, we can estimate the rate and duration of the particular stages of sedimentation and reconstruct the history of the development of complex natural systems, such as floodplains. It is important that the degree of soil development on the floodplains depends on the rate of alluviation. Soils are formed during periods of low rates of alluviation (in Eastern Europe <1 mm/year), and well-developed zonal soils such as Luvisols and Chernozems can form when rates are <0.1 mm/year.

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