Resoiling on Anthropogenically Disturbed Surfaces in the Southern Taiga Subzone

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Abstract—Based on investigating dated anthropogenic structures, we present the results derived from studying the development features of soddy podzolic soils over the course of the first 600 years from the zero time of soil formation. A commonness of the chronological regularities has been ascertained for the reproduction of morphological structure of soddy podzolic and chernozemic soils.

Keywords: soil formation rate, humus horizon, southern taiga, soddy podzolic soils, modeling.

FORMULATION OF THE PROBLEM

Anthropogenic disturbances to soil cover in the era of industrial development of society have become a widely occurring factor driving natural regeneration processes from the zero time. Formation of newly emerged soils on disturbed or man-made surfaces, together with progressive successions of the biota, lies at the basis of the regeneration dynamics of ecosystems. The zonal conditions for occurrence of these processes determine the features peculiar to the attainment of a stable (quasi-climax) state of ecosystems and their components.

Newly formed soils on anthropogenically disturbed surfaces have been time and again the subject of pedogenic investigations in the subzones of the middle and southern taiga [1–5]. The main results of those research efforts can be summarized in the following statement: the first few decades of pedogenesis develop almost the entire complex of morphofunctional attributes of young soils, which makes it possible to diagnose the directedness of their evolution into zonal soil subtypes. Abakumov et al. [5] compared the properties of uneven-aged soils of technogenic landscapes in the Leningrad oblast which had formed during the first few decades. However, to re-veal the ontogenetic regularities of pedogenesis dictates a need to consider relatively long chronoseries of soils; otherwise the conclusions concerning the characteristic time of occurrence of soil-regeneration processes will be insufficiently justified. The investigations made in the middle-taiga subzone of West Siberia [6] examined the newly formed soils between 1500 and 2700 years old which more fully reflect the preclimax stages of recent pedogenesis when compared with the soils dated at $n \cdot 10$ years. Nonetheless, the investigations just cited point out that the morphofunctional organization of the profile of the soils used in this study.

To date an optimal (as regards statistical indicators) body of soil-chronological information (covering more than 350 objects) has been accumulated for zonal conditions of forest-steppe. The results from analyzing such information are reported in a monograph [7].

The objective of this study was to implement for the southern taiga conditions the approach in investigating the natural reproduction of soils as developed by these authors and tested previously in the forest-steppe zone [7].

OBJECTS AND METHODS OF INVESTIGATION

The study area includes the western part of the Slantsy district and the southern part of the Kingisepp district of Leningrad oblast. The territory is within the southern-taiga subzone of soddy podzolic soils and forms part of the Baltic province of soddy podzolic, weakly humificated soils. In accordance with the new classification of soils of Russia [8], the background soils on the territory under investigation are assigned to the order of alpha-humus soils, the type of soddy podzols which are largely represented by subtypes of ferrous-illuvial and pseudo-fibrous soils. In this paper, we have adhered to a conventional soil classification and a traditional indexation of soil horizons [9].

The study territory has a transitional (from maritime to continental) climate. The average January and July temperatures are 7 and 15ºC, respectively. An annual precipitation amount is as large as 850 mm. The value of radiation balance is 1382 MJ/(year · m^2). The calculated values of expenditures of energy for soil formation [10] in the study area are estimated at 924 to 993 MJ/(year · m^2).

The investigation is concerned with a chronological series (pedochronoseries) comprising 18 soils that formed on surfaces of different origins: rock spoil heaps of JSC "Leningradslanets" (sections 1–5); areas disturbed by civil engineering work (sections 13, 15, and 18); defense structure dating back to the Great Patriotic War (sections 14 and 17); the ruins of the Yamburg fortress in the city of Kingisepp (section 14), and kurgans (burial mounds) from the 11th–14th centuries (sections 7–12) (Fig. 1).

The soil formation onset was dated by the historical method using documented evidence on the cessation of anthropogenic activity, including data from archaeological summaries [11, 12].

Because of the great diversity inherent in the substratum-phytocenotic and topological conditions of the objects used in the study, we described, as an arbitrary zonal analog, the soddy moderately podzolic sandy-clay soil on stratified fluvioglacial deposits under the canopy of secondary birch-pine forest with common wood-sorrel (*Oxalis acetosella*) (0.5 km from the village of Gorbovo, Slantsy district, section 6). Its morphological attributes and physicochemical properties that reflect the status close to the climax stage were used as a reference object in interpreting the properties of the newly formed soils developing on sandy parent rock.

A distinctive feature of the approach implemented in investigating natural reproduction of soils involves using the models of recent (new) pedogenesis in order to substantiate reproduction of soils and gain a correct understanding of the rate of this process.

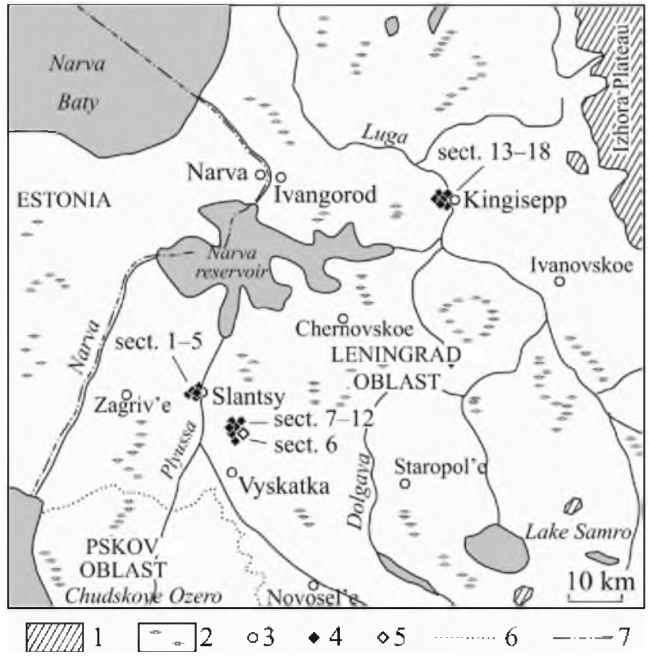

Fig. 1. Objects of soil-chronological investigations on the territory of the Leningrad oblast.

(1) elevations; (2) swamped lowlands; (3) residential centers; (4) points of establishing sections of newly-formed soils; (5) place of establishing the soil section – zonal analog. Boundaries and border: (6) boundaries of subjects of the Russian Federation, (7) state border.

RESULTS AND DISCUSSION

Recent pedogenesis results in reproduction of the morphological structure and functional organization of the disturbed soil profile (Table 1). If, as a consequence of a local disturbance, the type of soil-forming material and the biogeocenotic environment remain unaltered, then the newly formed soil at the final (close to climax) stage of development will correspond to the background soil in its texture and properties. The various lithological conditions of technogenic spoil heaps, with the leading elementary pedogenesis processes (EPP) of the zonal (bioclimatic) type of soil formation being unchanged, can give rise to new elements in the structure of soil cover on a disturbed territory. It is suggested in [13] that "continuity" of soils in disturbed areas in reference to background soils remaining unchanged should be assessed from the degree of reproduction of "soil matrix", i.e. a sequence of soil horizons. For soddy podzolic soils this "matrix" has a standard form: A0–A1–A1A2–A2–A2B–B–BC.

Newly formed soils reproduce, even though asynchronously) the zonal sequence of pedogenic horizons regardless of the type of parent rock (see Table 1). Inspection of the series of newly formed soils with similar particle-size (largely supes) composition permits us to determine the following sequence of formation of the soil profile within the chronointerval from 6 to 600 years used in this study:

I. 6 years: A0–(A1 + A1A2)–AC.

II. 15–30 years: A0–A1–A1A2–A2B–BC.

III. 30–600 years: A0–A1–A1A2–A2–A2B–BC.

IV. Full-age analog: A0–A1–A1A2–A2–A2B–B–BC.

In [5], where the results of soil formation on loamy substratum are discussed for similar bioclimatic conditions (technogenic landscapes of the Kingisepp district), the eluvial part of the profile in the soils between 10 and 19 years was not diagnosed by the authors. Our investigations into the morphology of young souls suggest that, in the presence of substratum containing significant amounts of earthly matter, an early (6–15 years) eluvial-illuvial organization of the profile of newly formed soils is possible.

Variation of the soil-formation factors can accelerate or decelerate the origination of some genetic horizons of soils. With the involvement of herbaceous vegetation, for example, the humus-accumulative horizon (A1) appears earlier and is more pronounced than under forest vegetation (see Table 1, sections 13 and 15 against sections 5/1–5/3 and 5/5). Content of carbonates in parent rock (in the form of carbonate rubble, for example) acts to decelerate separation of the A2 eluvial horizon (see Table 1, section 14).

Time variation of the role and intensity of the individual EPPs can be characterized in terms of the

Table 1. Morphological structure of the profile of newly-formed soils

Section number	Age, years	Type of parent rock*	Depth of lower boundary of soil horizons, mm**						
			A0	A1	A1A2	A2	A2B	B	BC
3	6	R_C	25	17 ± 7***		–	36 ± 12 (AC)	–	70 (C)
1	15	FS_C	27	20 ± 3	36 ± 4	–	64 ± 5	–	89 ± 5
2	15	SR_C	10	30	62	–	90	–	120
13	19	FS_C	10	38 ± 7	83	–	96 ± 35	–	170
15	24	L_L	5	41 ± 5	97 ± 15	–	232 ± 11	–	390
5/1	32	SR_C	20	14 ± 5	37 ± 7	85 ± 9	122 ± 11	–	164 ± 8
5/2	32	SR_C	25	19 ± 5	–	90 ± 10	119 ± 13	–	170 ± 4
5/3	32	SR_C	20	14 ± 8	–	88 ± 11	130 ± 2	–	178 ± 7
5/4	32	SR_C	15	21 ± 6	33	65 ± 22	90 ± 11	–	162 ± 11
5/5	32	SR_C	15	18 ± 7	58 ± 7	100 ± 9	145	–	180
16	60	S	10	65 ± 8	123 ± 9	–	272 ± 41	–	Undet
17	60	EH	5	62 ± 5	140	234 ± 12	320 ± 24	–	453 ± 13
17/1	74	FS	–****	79 ± 8	131 ± 19	282 ± 7	Undet	Undet	Undet
18	134	FS	5	98 ± 5	168 ± 9	325 ± 16	444 ± 21	–	694 ± 12
14	188	R_C	8	90 ± 9	183 ± 8	–	245 ± 11	–	275
10	600	EH	30	96 ± 9	168 ± 22	332 ± 23	486 ± 13	690	Undet
11	600	FS	25	103 ± 11	174 ± 22	369 ± 24	490 ± 39	700	1260
12	600	EH	25	101 ± 14	164 ± 24	390 ± 43	650	740	Undet
6	Undet	FS	20	150	210	430	620	970	Undet

* FS – friable sand; FS_C – friable carbonate sand; CS – consolidated sand; LS – loamy sand; L_L – light loam; SR_C – sand with limestone rubble; R_C – carbonate rubble; EH – embankment of humusified material, S – sand.
** When there are measurements in replications, confidence intervals of samples ($\bar{x} \pm t_{05}S$) are given.
*** Separation of the soil profile in individual horizons is difficult.
**** The pedogenic horizon is not pronounced.

relationship between the thicknesses of the humus-accumulative, eluvial and illuvial parts of the soil profile (A1 + A1A2 : A2 + A2B : B + BC). In the zonal soil, it has the form 1 : 2 : 4, which gives evidence of the predominance of eluvial-illuvial soil-formation processes. In the soils of the chronoseries, such a proportion is attained for 600-year-old soils. The first few decades of soil formation more commonly show a ratio close to 1 : 2 : 1. Under herbaceous vegetation, the leading EPPs exhibit a more balanced behavior (1:1.5:1.5). Early in the development of soddy podzolic soils, eluviation products appear to be transported beyond the zone of primary, chronologically separable, layer of the soil profile. Therefore, illuvial horizons are formed more slowly than eluvial ones. In general, the completion of morphological organization of the profile of the soils under investigation has a characteristic time of n·100 years.

There are several approaches in calculating the characteristic time of soil-formation processes. Thus, on the basis of a computer simulation [14], it was established that according to the amount of annual litter and organic matter reserves in genetic horizons of soddy podzolic soils, the characteristic time is 20 years for the A0 horizon, 60 for the A1 horizon, and 80 years for the AB, B and BC horizons. Using an extrapolation method, it was found in [6] that the characteristic times of the processes characterizing the eluvial-illuvial differentiation of the podzolic soil profile fall within the range from 1500 to 8000 years. From our point of view, to gain proper insight into the regularities of development of the soil properties over time, mathematical models developed on the empirical basis of soil-chronological data would be appropriate.

Lisetskii in his monograph [15] substantiated the use of a class of S-shaped functions to model the formation processes of soil horizons over time as well as showing that it is worthwhile using in describing the evolution of the soil as a biotic/abiotic system a class of growth functions which were successfully tested previously, as applied to biological systems. Taking into consideration the theoretical ecological-resource concepts of the soils and the prospects for practical implementation of the results, modeling of the process of shaping the humus profile of soils is of utmost current importance. To this end, we modeled the thickness of the humus horizon for the soils in anthropogenically disturbed landscapes under investigation (we designate the total thickness of the A1 + A1A2 horizons (mm) for the particular soil age t, as H_t).

The model describes the dynamics of frontal descending humification of initial substratum, i.e. a set of organic-mineral interactions that are responsible for the movement of the lower boundary of the humus horizon. As the approximating function, we used the growth function of a generalized form [16] and, upon substantiating the possible simplification, the Gompertz function (Fig. 2) having the form:

$$H_t = H_{S\text{-}LIM} \cdot \exp(-\exp(a - \lambda t)) ,$$

where $H_{S\text{-}LIM}$ is the ultimate thickness of the H humus horizon under particular bioclimatic conditions for a definite particle-size composition of soil-forming materials (assuming 210 mm, corresponding to an arbitrarily taken background soil); t is the soil-formation time, years; a is a constant reflecting the initial conditions of the soil-formation process, and λ is a constant dependent on bioclimatic conditions of pedogenesis.

To correctly construct the chronoseries of the soils, the values of the thickness H were recalculated with a correction for the equilibrium volumetric mass determined for the A1 horizon of an arbitrarily taken background soil. The soils of the chronoseries for which the measurements of the thickness H were made in replications, are specified by two points reflecting the boundaries of the confidence interval of the samples.

Determination of the key times of the H formation process is possible when investigating the model obtained following the scheme described in [16]. The main H growth phases are determined by the points T_1 (onset of growth, maximum acceleration of the process), T_2 (middle, maximum of growth rate) and T_3 (completion of growth, minimum acceleration of the process). In the resulting model, T_1 corresponds to soils 4 years old, T_2 to 46 years, and T_3 to 88 years (see Fig. 2).

The starting stage of H formation (0–6 years) is characterized by a relatively fast transformation of plant litter (A0) into the organic-mineral horizon, with the result that the average rate of this process (obtained by dividing the thickness H by the age) varied from 3 to 6 mm/year. This chronointerval is not described by the model; therefore, a calculation of "instantaneous" rates of the process is only possible starting with the soil age of 4–6 years. It may be suggested that, upon completion of the initial (0–6 years) formation of the humus horizon, its growth rate decreases dramatically. After that, within the time interval from 4–6 to 46 years, the H growth rate decreases to 1.76 mm/year, and subsequently to 1.25 mm/year, starting from the chronopoint T_3. After 200 years of pedogenesis the rate of H formation becomes below the value 0.14 mm/year.

Upon analyzing the modeling results, it was established that a stabilization of the formation process of the humus horizon of soddy podzolic soils occurs as early as at the age of 80 years. Note that in the case of forest-steppe chernozems, a stabilization of growth of the humus horizon (A + AB = H) at the early stage of this process occurs within 70 years of pedogenesis; however, the stage with the predominance of the eluvial-illuvial mechanism of H growth lasts longer than 5000 years [17]. The analysis of the "instantaneous" (calculated in the model) growth rate of the H horizon of soddy podzolic soils showed that the values of this indicator compare with those obtained previously for the conditions of recent pedogenesis in the forest-steppe zone, but the maximum rate is attained 10–15 years later when compared with chernozems (Fig. 3).

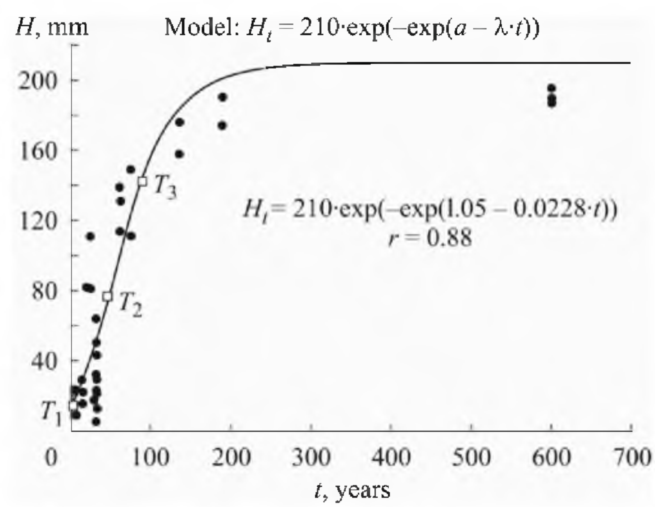

Fig. 2. Time dependence of formation of the humus horizon (H) of soddy podzolic soils (t).

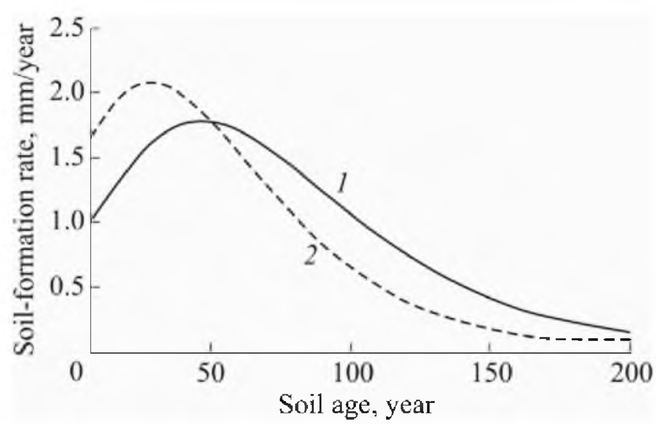

Fig. 3. Formation rate of the humus horizon of soddy podzolic soils *1* and chernozems of forest-steppe *2*.

Table 2. Physicochemical properties of uneven-aged soils from the southern taiga

Horizon	Depth, cm	Humus, %	Nitrogen, total, %	C/N	pH (KCl)	Sum of absorbed bases	Hydro-lythic acidity	Fe_2O_3, % (acc Tamm)
						mmol/dm in 100 g of soil		
Section 15 (soil age of 24 years)								
A1	0–4	3.38	0.162	12.1	7.07	23.92	0.98	0.22
A1A2	4–10	1.39	0.014	57.5	6.63	8.64	0.65	0.21
A2B	10–23	0.36	0.021	9.9	6.56	4.42	0.33	0.23
BC	23–39	0.30*	0.035	5.0	6.52	6.23	0.56	0.38
Section 18 (soil age of 134 years)								
A1	0–10	3.93	0.056	40.6	7.10	34.37	0.33	0.70***
A1A2	10–17	1.86	Traces	–**	7.19	5.5	0.33	0.60
A2	17–33	0.13	0.049	1.5	6.94	3.22	0.49	0.11
A2B	33–44	0.24	0.077	1.8	6.90	2.21	0.49	0.12
BC	44–69	0.12	0.035	2.0	6.61	3.82	0.33	0.07
Section 11 (soil age of about 600 years)								
A1	0–10	4.63	0.084	31.9	6.39	21.31	1.63	0.36
A1A2	10–17	1.98	Traces	–	5.03	8.64	3.59	0.22
A2	17–37	0.50	0.074	3.9	4.66	2.01	2.28	0.17
A2B	37–49	0.45	0.092	2.8	4.63	1.91	1.79	0.23
B	49–70	0.27	Traces	–	4.87	2.61	1.30	0.32
BC	70–126	0.36*	0.024	8.7	5.42	5.43	1.47	0.28
Section 6 (zonal soil)								
A1	0–13	4.63	0.032	83.8	6.00	22.11	3.42	0.46
A1A2	13–19	1.69	0.035	28.0	5.55	8.24	2.44	0.38
A2	19–41	0.39	0.021	10.8	5.04	4.42	1.63	0.12
A2B	41–60	0.12	Traces	–	4.83	1.01	1.14	0.10
B	60–97	0.13	0.081	0.9	5.71	8.54	0.65	0.53
BC	Over 97	0.13	Traces	–	5.35	4.22	0.81	0.12

* The soil of railroad embankment is characterized by elevated carbon content.
** The soil of railroad embankment contains technogenic iron.
*** A calculation of the C/N ratio is impossible because of the minimum amount of nitrogen.

Hence, some difference in the expenditures of energy for soil formation (averaging 100 MJ/(year·m^2)) in the forest-steppe zone and in the southern-taiga does not lead to any substantial difference between the formation rates of the humus horizon of soils in these natural zones in the chronointerval 0–100 years.

Reproduction of the morphological structure of the soddy podzolic soil profile is accompanied by its functional organization whose results are manifested in a directed change in chemical properties (Table 2). As the Table 2 data suggest, starting in almost the first few decades of formation, the soddy podzolic soils have had a zonal character of profile distribution of the chemical properties: regression-accumulative for humus and total nitrogen, and accumulative-eluvial-illuvial for the sum of absorbed bases, and for iron. With increasing age, there is an enhancement in the acidity of soils, which increases the intensity of eluvial-illuvial processes. The 600-year-old soil shows an almost total completion of the functional organization of the profile, and the development of the B and BC horizons is in progress.

CONCLUSIONS

The analysis of the morphological and functional attributes of the newly formed soddy podzolic soils on anthropogenic surfaces suggests the following conclusions.

It was found that the bioclimatic energy potential of pedogenesis predetermines from the outset the formation of a genetic "matrix" (a sequence of pedogenic horizons) of background soddy podzolic soils; therefore, the development of soils within a zonal pedogenic series can be diagnosed already during the first few decades.

Essentially the entire set of embryonic horizons has its origin in the first few decades (10–30 years) of pedogenesis as well, with the organization and isolation of the humus-accumulative (A1) and eluvial (A2) horizons occurring earlier when compared with the illuvial part of the profile.

The zonal differences in formation conditions for chernozemic and soddy podzolic soils notwithstanding, there is a commonness of the regularities of their reproduction across time, i.e. the processes of morphological organization (development of the ontogenetic program) obey the general kinetic regularities.

These conclusions substantiate the possibility of elaborating unified principles of managing natural reproduction of soil resources in anthropogenic geosystems which take into consideration the ontogenetic regularities of the early stages of recent pedogenesis.

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