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Typification of Soil Catenas on Slopes from the Quantitative Manifestations of the Accumulation and Loss of Soil Material

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Abstract—A typification of soil catenas on slopes from the manifestations of soil erosion and accumulation processes studied at several key plots in the central part of the East European Plain and in the Mid-West of the United States is suggested. The magnetic tracer method was used for assessing the rate of lateral mechanical migration of the products of pedogenesis. The typification of soil catenas on slopes was performed with the quantitative consideration for the material loss and accumulation rates, the degree of openness of the soil catenas for the migration fluxes, and the localization of accumulation zones on the slopes.

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RELEVANCE AND GOALS OF THE STUDY

The analysis of soil erosion–accumulation processes is of great importance for geographical soil science and environmental geochemistry. The quantitative parameters of these phenomena and their manifestation under the impact of various natural and technogenic factors are essential for our understanding of the nature of mechanical migration, one of the most widespread and significant forms of material migration. The flows of solid-phase soil components result in the significant differentiation of the soil cover into the areas of denudation and accumulation, accelerate or slow down the formation of vertical soil profiles, and create specific soil combinations within catchments of different levels. The need for a more thorough study of the denudation–accumulation processes in the context of the challenges of geographical soil science and environmental geochemistry was repeatedly emphasized by Maria Al'fredovna Glazovskaya [8]. She suggested that the ratio of the areas occupied by transeluvial landscape facies with eroded soils on slopes and by transaccumulative (footslopes) and accumulative (depressions) landscape facies could be used as a characteristic of the dispersion and concentration of the solid-phase products of pedogenesis. She noticed the importance of considering the quantitative proportions between the masses of sediments accumulated within and beyond the slopes, as well as the scientific promises of these proportions for understanding the nature of the entire system of soil migration processes. At the same time, Glazovskaya noted that "the worldwide denudation–accumulation patterns of the soil cover are insufficiently studied as cascade spatial dynamic systems," and new approaches aimed at their study, classification, and mapping should be developed [8].

In fact, a number of different approaches to the classification of soil-geochemical catenas and soil catenas on slopes have been developed by now [7, 13–16, 19–22, 24]. However, the processes of soil erosion–accumulation are considered only in a general form; they are directly taken into account in few classification systems. Milne [27] was one of the first scientists to take into consideration the erosion–accumulation processes in the classification of soil catenas on slopes. He introduced the term "soil catenas" and considered the erosion of soils as an important factor of their formation.

In the nine-element model of the earth's surface developed by Dalrymple et al. [24], the mobilization, translocation, and redeposition of material by surface flows are the decisive factors in some cases. However, this model is based exclusively on the geomorphological approach and ignores any factors of material's migration, except for the surface topography.

The classification of geochemical landscapes by Perel'man [18] includes eight taxonomic units: series, group, type, division, family, class, genus, and species. Mechanical migration processes are considered at the genus level, where he distinguishes flat plains with slowed water exchange and with low erosion dissection (genus I); eroded elevations, dissected plateaus, etc., with more intense surface and soil runoff (genus II); and strongly dissected mountainous relief, badlands, etc., with the most intensive water exchange (genus III). This separation of the genera according to the mechanical migration rate allows classifying geochemical landscapes only at the large-scale regional level. At the same time, the rate of the mechanical migration and its effect on the structure of the geochemical landscapes within each genus are extremely diverse.

Later on, Kasimov and Perel'man [14] proposed an additional taxonomic unit (variety) to be distinguished. This unit is not directly destined for the more detailed consideration of mechanical migration in the classification of geochemical landscapes. However, its use can form the methodological basis for the further development of approaches to the analysis of the material loss–accumulation processes with a view of systematizing geochemical landscapes. The authors separated nine varieties in accordance with the matrix conjugation principle of three options of the lateral-migration differentiation and three options of the lithogeochemical differentiation. The main criterion for the separation of the varieties is the coefficient of lateral differentiation (L) equal to the ratio between the element content in the geochemically subordinate landscape to its content in the autonomous landscape. It was noted that different groups of chemical elements could have specific ratios in the catena. Thus, elements with very low coefficients of water migration, which migrate only (Al, Ti, Ga Th, Sc, and Pb) or predominantly (Si, Fe, Mn, P, Ba, Zn, Rb, Cr, Co, and Ni) in suspensions, can be considered as markers of the mechanical migration of material during the separation of the varieties.

In Glazovskaya's geochemical classification [7], local landscapes are subdivided into eight taxonomic levels. During the separation of landscapes at the type level, soil water erosion, land sliding, deflation, and other landscape types are distinguished. However, at lower taxonomic levels (subtype, species, subspecies), landscapes are not classified in more detail in accordance with the rate of the mechanical or other forms of migration.

In this paper, data on the quantitative assessment of soil erosion–accumulation are generalized. They were obtained by the authors using the new magnetic tracer method in the study of soil catenas on slopes in different regions of the forest and forest-steppe zones on the central East-European Plain and in the Mid-West of the United States.

The goals of the work were to calculate and compare the lateral mechanical migration rates of soil material under different conditions of land use (under forest, steppe, and cultural vegetation); to analyze the spatial confinement of the removal and accumulation zones of the pedogenesis products in relation to the morphology and aspect of the slopes; and, finally, to classify the soil catenas on slopes on the basis of the erosion–accumulation manifestations. It should be emphasized that only the mechanical migration of soil material under the impact of temporary surface water runoff, which is the leading process of the mechanical migration of soil material in the areas under study, is considered below.

METHODS AND OBJECTS OF STUDY

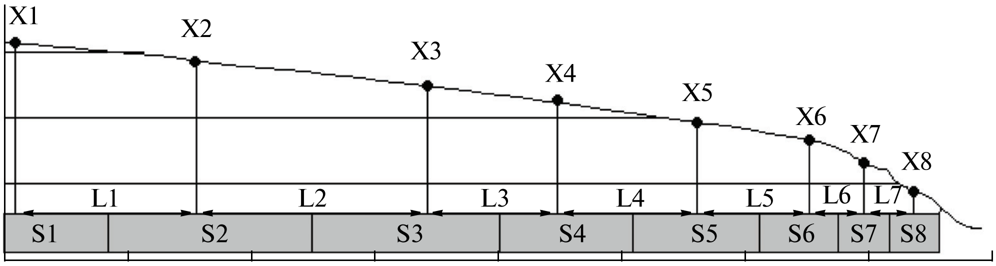
The magnetic tracer method was applied to the study of soil erosion in the United States about 20 years ago [25] and in Russia 10 years ago [6]. The method is based on the quantification of the redistribution of spherical magnetic particles (SMPs) in soils. The intensive input of technogenic SMPs onto the surface of the soil cover in the industrially developed countries began with the appearance of the first railroads and steam locomotives, i.e., about 150 years ago. Studies showed that, near railroads, this source of SMPs significantly predominates over various natural (volcanic emissions, space fallouts) and technogenic (different pyrolytic industrial processes related to the burning of coal) sources.

SMPs are stable and relatively inert substances in the soil material. In the soils with predominant oxidative conditions, they undergo no visible degradation for a long time (at least over hundreds of years). SMPs mainly consist of magnetite, hematite, and other iron minerals. The size of the particles varies from fractions of a micrometer to hundreds of micrometers. Some features of magnetic particles, such as their shell structure, cavitation, and metallic luster distinguish them from many other strongly magnetic minerals [5].

Within local areas, SMPs relatively uniformly arrive from the atmosphere to the soil; therefore, changes in their concentration in the soil cover are due to their redistribution and the erosion–accumulation of soil material. It is supposed that the mass of the magnetic tracer redistributed because of lateral mechanical migration is directly proportional to the mass of the redistributed soil material. The determination of the SMPs in the soil includes the separation of the magnetic fraction from the soil and the microscopic calculation of the SMPs. The quantitative estimation of the soil erosion rate is based on the comparison of the SMP concentrations and reserves on different segments of slopes with those in the reference watershed positions with consideration for the segment lengths and the time of occurrence of the SMPs in the soil (from the beginning of the active use of steam engines on the railroads near the studied plot, usually 100–150 years ago).

The procedure for the separation and quantification of soil SMPs includes the quantitative wet separation of the magnetic fraction from the soil material and its microscopic analysis (magnification 600–1200×). The volume concentration of the magnetic particles 1–53 μm in size in the magnetic fraction was assessed using a MiniVid digital camera and the corresponding software.

The volume of the removed or accumulated soil material was calculated from the imbalance of the soil material on different slope segments compared to the watershed areas. The calculation was performed for linear slope segments, whose lengths depended on the density of the sampling sites or, in the case of aerial testing, for aerial segments separated in accordance with the morphological homogeneity of the slope segments using a topographic map and a surface slope map. The translocation rate of the material was determined by dividing the difference between the SMP



Scheme of the slope segmentation: (*X*) sampling sites; (*L*) distance between the sampling sites; (*S*) slope segments.

reserves by the number of years elapsed since the input of the SMPs into the soil (the year of the beginning of the exploitation of the nearest railroad in the 19th century was usually taken). We shall consider the methods of calculating the mechanical migration of the soil material in more detail on the basis the following example. Let eight sampling points be established on the slope (figure).

The reserves of SMPs were $X1$ g/m^2 at site 1, $X2$ g/cm^2 at site 2, ..., and $X8$ g/cm^2 at site 8. The distance between sites 1 and 2 was $L1$; the distance between sites 2 and 3 was $L2$, etc. Each sampling site characterized a certain slope area (segment) where the conditions of the mechanical migrations were relatively uniform. For relatively regular slope inclinations, the segment length was calculated from Eq. 1:

$$S_n = \frac{L_{(n-1)}}{2} + \frac{L_n}{2}. \qquad (1)$$

The mass of the redeposited soil material V (in tons) was calculated from Eq. 2:

$$V = \frac{(Xn - X1)\,MSn\rho}{X1 \times 100}, \qquad (2)$$

where $X1$ is the reserve of SMPs in the soils of the flat watershed area, g/m^2; Xn is the reserve of SMPs in the soils of the studied slope segment, g/m^2; M is the thickness of the sampled layer (or the penetration depth of the SMPs), m; Sn is the area of the sampling segment, m^2; and ρ is the soil density, g/cm^3 or t/m^3.

The mass V corresponds to the total amount of the redeposited material on the nth slope segment; it has a negative sign at the predominant removal of material and a positive sign at the predominant intraslope accumulation.

In the calculation of the deposit budget on small and relatively uniform slopes, one can take the transect width as 1 m and recalculate the total mass of the redeposited material for the area. Dividing the obtained value by the number of years of the SMP fallout, we obtain the average migration rate of the soil material T (Eq. 3):

$$T = \frac{\sum V \times 10000}{\sum LP}, \qquad (3)$$

where T is the mechanical migration rate of the soil material during the period of the SMP fallout, t/ha per year; ΣV is the total volume of the redeposited material in all slope segments, t; 1000 is the factor to recalculate from m^2 to ha; ΣL is the total slope length, m (for the transect width being taken as 1 m, it corresponds to the sampling area, m^2); and P is the occurrence time of the SMPs in the soil, years.

The principles of calculating the lateral mechanical migration rate of the pedogenesis products using this method, as well as the method's features in comparison with other methods for the quantitative estimation of soil erosion–accumulation, were described in more detail earlier [3].

The presented results are based on the data obtained in the study of soil catenas on slopes on eight key plots in the forest and forest-steppe zones of the central East-European Plain and in the Mid-West of the United States (Table 1). More detailed descriptions of these key plots and the results of studies were reported earlier [3, 4, 10, 28].

The studied soil catenas were mainly tested along three duplicating transects spread at 3-m intervals along the slope beginning from the flat near-watershed area to the foot of the slope. More than 200 soil profiles were studied, and about 4500 soil samples were analyzed.

RESERVES OF SMPS IN THE STUDIED SOILS ON SLOPES AND THE LATERAL MECHANICAL MIGRATION RATE OF THE SOIL MATERIAL

Using the magnetic tracer method, we obtained data characterizing the reserves of SMPs in soils and the mechanical migration rate of the soil material on different parts of the slope for all of the plots studied (Table 2). The numbers of the soil profiles on each plot in Table 2 go top down, from the watershed surface to the foot of the slope.

In Table 3, the average migration and accumulation rates of the soil material on the slopes are given with account for the lengths of the different slope segments, as well as the percentage of material removal beyond the slopes.

Table 1. Physiographic conditions of the plots

No.	Plot (oblast/state)	Index	Shape, length, slopes	Parent rocks	Soils	Land use
1	Yamskaya Step' (Belgorod)	BY	concave, 550–750 m, to 5°	calcareous loess-like loams	typical chernozems	plowland; grass-herb steppe
2	Elektrougli (Moscow)	ME	concave, 300–350 m, to 3°	glaciofluvial sands and loamy sands on moraine	soddy-podzolic soils	plowland
3	Springfield (Illinois)	IS	concave–convex, 2500–3000 m, to 3°	deep-calcareous lows-like loams	leached chernozems; plowland	plowland; herbaceous maple-oak forest
4	Hannover (Illinois)	IH	concave–convex, 300–400 m, to 11°	"	lessivated burozems	plowland; herbaceous maple-oak forest
5	Gracheva Loshchina (Kursk)	KG	concave and concave–convex 500–600 m, to 5°	@Карбонатные лёссовидные суглинки	leached and typical chernozems	plowland
6	Aleksandrovka (Tula)	TA	concave, 400–500 m, to 6°	"	podzolized and leached chernozems	"
7	Tolmachi (Tambov)	TT	concave, 450–600 m, to 3°	"	leached and typical chernozems	"
8	Zhdanovka (Orel)	OG	straight 800–900 m, to 7°	low-calcareous loess-like loams	podzolized and leached chernozems	"

The analysis of the data presented allows conclusions to be drawn about the quantitative parameters of the mechanical migration of the soil material under different land-use conditions. Using the direct magnetic tracer method, we performed the comparative quantitative analysis of the erosion–accumulation manifestations in arable and fallow soils of numerous regions in Russia and the United States. Thus, in typical chernozems of the Yamskaya Step' plot and leached chernozems of the Springfield plot, the loss of soil under the natural vegetation by erosion was not manifested or did not exceed 3 t/ha annually. On morphologically identical slopes with analogous but tilled soil cover, the mechanical migration rate of the soil material increased by an order of magnitude and more. The tillage of the Yamskaya Step' plot resulted in an increase in the loss of typical chernozems from some slope areas to 25 t/ha per year and more; the loss of leached chernozems of the Springfield plot was 14 t/ha per year and more. Studies performed on lessivated burozems of the Hanover plot in the state of Illinois (USA) showed high rates of soil erosion under both plowland and forest. They approached 12 t/ha per year under forest vegetation and reached more than 19 t/ha per year under plowland. The high erosion level of the forest soils could be related to their probable tillage in the late 19th and early 20th centuries, as was evidenced by the morphological properties of the soil profiles and the radial distribution of the SMPs. The SMP distribution was found to be of uniform character in distinction from the surface-accumulative distribution typical for anthropogenically undisturbed soils under forest vegetation.

The data in Tables 2 and 3 characterize the location of soil erosion–accumulation zones on arable slopes with different morphologies: convex and convex-concave (convex in the upper part of slope and concave in its lower part) longitudinal profiles of slopes.

Concave–convex arable slopes were examined on the basis of studying the lessivated burozems in the Hanover plot, leached chernozems in the Springfield plot, and typical chernozems on a slope of the Gracheva Loshchina plot (KGCR2, KGC52-57). The literature data on the study of lessivated burozems in the Dixon-Springs plot in the state of Illinois (USA) [26] were also used. It was found that the alternation of erosion and accumulation zones was observed for arable soils in the upper part of such slopes from watershed areas to the upper steepest part of the slope. The localization of the erosion and accumulation zones was differently manifested in different plots. Removal of arable soil material from the watershed part of the slope and accumulation of sediments on its shoulder were observed in the Dixon-Spring plot. In the Gracheva Loshchina plot, on the contrary, erosion of the slope's shoulder and the accumulation of sediments in the upper steepest part of the slope were observed. In all of the studied plots with concave–convex slope profiles, the reserves of SMPs in the lower concave parts of the slopes were 1.5–7 times smaller than those in the soils of the watershed areas. For example, the SMP reserves in the burozems of the Dixon-Springs plot were 15.6 g/m^2 in the watershed areas, 16.5–23.3 g/m^2 in the upper (concave) part of the slope, and only 4.9–9.7 g/m^2 in its lower (concave) part. In leached chernozems of the Springfield plot, the reserves of SMPs were 33.4 g/m^2 in the watershed

Table 2. Reserves of spherical magnetic particles (SMPs) in soils and the mechanical migration rate of soil material (SMMR) in different slope segments

Profile	Layer, cm	SMP reserve, g/m^2 in the layer	SMMR, t/ha per year
Gracheva Loshchina plot			
KGCR3	25	2.4	0
KGC 30	25	1.9	–6*
KGC 31	25	3.3	11
KGC 32	25	1.9	–6
KGC 33	25	1.9	–6
KGC 34	25	2.3	–1
KGC 24	25	2.3	0
KGC 25	25	2.7	4
KGC 26	25	0.9	–17
KGC 27	25	1.4	–11
KGC 28	25	0.6	–20
KGC 29	25	2.3	0
KGC 35	25	1.5	–9
KGCR2	25	1.5	0
KGC 52	25	1.0	–9
KGC 53	25	1.7	5
KGC 54	25	2.2	14
KGC 55	25	1.1	–8
KGC 56	25	1.0	–9
KGC 57	25	1.1	–7
Yamskaya Step' plot			
BYC11	30	17.6	0
BYC12	30	9.5	–17
BYC13	30	13.0	–9
BYC14	30	4.1	–27
BYC15	30	7.7	–20
BYC16	30	6.2	–23
BYS21	30	10.4	0
BYS22	30	12.5	2
BYS23	30	8.7	–2
BYS24	30	17.2	10
BYS25	30	6.8	–4
BYS26	30	12.0	2
Springfield plot			
ISC 1	30	33.4	0
ISC 2	30	24.8	–7
ISC 3	30	14.8	–14
ISC 4	30	26.6	–5
ISF 5	30	18.1	0
ISF 6	30	25.1	3
ISF 7	30	8.3	–5
ISF 8	30	12.3	–3
Zhdanovka plot			
OGC 1	25	2.6	0
OGC 2	25	0.8	–23
OGC 3	25	0.4	–27
OGC 4	25	0.2	–30
OGC 5	25	0.2	–30
OGC 6	25	0.1	–31
Hannover plot			
IHC 6	30	14.2	0
IHC 7	30	3.9	–19
IHC 8	30	3.9	–19
IHC 9	30	4.9	–17
IHF 1	30	8.9	0
IHF 2	30	9.5	0
IHF 3	30	8.2	–4
IHF 4	30	5.3	–12
IHF 5	30	5.5	–11
Elektrougli plot			
MEC 1	25	11.2	0
MEC 2	25	6.3	–10
MEC 3	25	10.7	–1
MEC 4	25	10.6	–1
MEC 5	25	15.9	10
MEC 6	25	13.5	5
Aleksandrovka plot			
TAC 1	25	4.1	0
TAC 2	25	7.3	20
TAC 3	25	4.5	3
TAC 4	25	4.1	0
TAC 5	25	2.2	–12
TAC 6	25	3.9	–1
TAC 7	25	4.7	4
TAC 8	25	5.7	0
TAC 9	25	3.8	–8
TAC 10	25	3.1	–11
TAC 11	25	3.1	–12
TAC 12	25	3.2	–11
TAC 13	25	3.1	–11
TAC 14	25	1.6	–18
Tolmachi plot			
TTC 1	25	1.1	0
TTC 2	25	0.5	–14
TTC 3	25	1.2	2
TTC 4	25	1.2	3
TTC 5	25	0.9	–4
TTC 6	25	1.1	0
TTC 7	25	1.1	2
TTC 8	25	1.0	–2
TTC 9	25	0.8	–6
TTC 10	25	0.6	–12

* The negative and positive values imply the removal and accumulation of material, respectively.

Table 3. Average migration and accumulation rates of the sloped soil material and the removal of material beyond the slopes of the plots studied

Plot	Index	Land	Aspect	Material migration rate, t/ha per year	Accumulation on the slope, t/ha per year	Material removal beyond the slope, %
Gracheva Loshchina	KGC	plowland	NE	3.9	2.7	31
	KGC	″	SW	9.5	1.1	88
	KGC	″	W	6.1	2.7	56
Yamskaya Step	BYC	″	N	18.2	0	100
	BYS	meadow	N	1.3	3.3	0
Springfield	ISC	plowland	SW	8.2	0	100
	ISF	forest	SE	2.6	0.9	65
Hannover	IHC	plowland	S	18.1	0	100
	IHF	forest	S	9.7	0	100
Elektrougli	MEC	plowland	W	3.1	2.2	29
Aleksandrovka	TAC	″	NW	1.8	4.7	0
	TAC	″	SE	11.1	0	100
Tolmachi	TTC	″	NW	4.2	1.3	69
	TTC	″	SE	5.9	0.3	95
Zhdanovka	OGC	″	SE	28.1	0	100

areas, 24.8 and 14.8 g/m^2 in the upper (concave) and lower (convex) parts of the slope, respectively, and increased to 26.6 g/m^2 to the foot of the slope. In typical chernozems on the slope of western aspect in the Gracheva Loshchina plot, the reserves of SMPs were 1.5, 1.0–2.2, and 1.0–1.1 g/m^2 in the watershed areas and the upper (concave) and the lower (convex) parts of the slope, respectively. The significant decrease in the SMP reserves in the lower convex parts of the slopes pointed to the development of erosion processes alone in the arable soils on these slope segments.

The active removal of soil material from the lower part of the concave slopes is explained by the nonlinear link law [17], according to which the discharge of sediments on a concave slope increases by two–three times compared to a convex slope after the merging of rills. Therefore, the parameters of the scours formed on these plots increase by more than two times [9].

Down the catenas, the removal rate of soil material in the lower foots of the slopes became slower. The discharge of flows and the removal of soil material to the river network occurred in the floodplain areas. The reserves of SMPs in the floodplain soils varied among the different plots, which was most probably related to the lengthwise removal or accumulation of soil material during the high water periods.

The analysis of the arable slopes with concave longitudinal sections was based on the study of soddy-podzolic soils of the Elektrougli plot, leached chernozems of the Aleksandrovka and Zhdanovka plots, typical chernozems of the Tolmachi plot, and typical chernozems on the slopes of southwestern and northeastern aspects of the Gracheva Loshchina plot.

On the concave slopes, the alternation of the erosion and accumulation zones of arable soils was observed throughout the slopes. The analysis of the location of these zones revealed no correlation with the slope aspect, any slope segment, or soil cover properties.

It was found that the soil catenas on the concave–convex slopes, where the migration rate of the soil material was lower than 10 t/ha per year, were characterized by the accumulation of material only in the upper part of the slopes; the removal of material was observed in the lower part of the slopes. For the soil catenas on the concave slopes with mechanical migration rates of the soil material lower than 10 t/ha per year, no confinement of the accumulation zones to any part of the catena was noted. The studied soil catenas with mechanical migration rates of the soil material higher than 10 t/ha per year were characterized by the absence of intraslope accumulation zones of soil material regardless of the slope profiles.

Table 4. Typification of soil catenas on slopes from soil erosion–accumulation manifestations

Soil material migration rate, t/ha per year	Soil material removed beyond catenas, %	Localization of accumulation zones			
		extra accumulation	upper accumulation	medium accumulation	low accumulation
<5 (hypodynamic)	>85 (extra open)	AI1			
	50–85 (open)		AII2	AII3	AII4
	<50% (semiopen)		AIII2	AIII3	AIII4
5–10 (mesodynamic)	>85 (extra open)	BI1			
	50–85 (open)		BII2	BII3	BII4
	<50 (semiopen)		BIII2	BIII3	BIII4
>10 (hyperdynamic)	>85 (extra open)	CI1			
	50–85 (open)		CII2	CII3	CII4
	<50 (semiopen)		CIII2	CIII3	CIII4

Note: Here and in Table 5, almost absent soil catenas on slopes are indicated by shading.

Another significant feature of the lateral mechanical migration of soil material is its different rates on slopes of different aspects. In steppe and forest-steppe, the rates of the soil loss on the slopes of warm southern and western aspects are higher than on the northern slopes. In addition, the slopes of southern aspect thaw more rapidly and remain unprotected for longer time periods, which increased the risk of erosion because of thaw water increasing the flow turbidity by an order of magnitude [1, 9]. The rate of the soil erosion–accumulation on slopes of different aspects was studied in three key plots: Aleksandrovka, Tula oblast; Gracheva Loshchina, Kursk oblast; and Tolmachi, Tambov oblast. The maximum steepness of the slope was 6° in the Aleksandrovka plot and 5° in the Gracheva Loshchina plot; the Tolmachi plot was characterized by gentle slopes with a steepness of no more than 3°.

It was found using the magnetic tracer method that the removal rates of arable soil material beyond the slopes under study were as follows: for leached and podzolized chernozems of the Aleksandrovka plot, 11 and 2 t/ha per year on the southern and northern slopes, respectively; for the typical and leached chernozems of the Gracheva Loshchina plot, 10 and 4 t/ha per year on the southern and northern slopes, respectively; and, for the typical and leached chernozems of the Tolmachi plot, 6 and 4 t/ha per year on the southern and northern slopes, respectively (Fig. 1).

Thus, the rates of the soil erosion are higher on the slopes of southern aspect than on the slopes of northern aspect. In the plots with slopes of 5° and 6° (Gracheva Loshchina and Aleksandrovka), the differences between the soil erosion rates on the different slopes were 2.5 to 6 times. On the gently sloped surfaces with steepness lower than 3° of the Tolmachi plot, the differences between the soil erosion rates on the different slopes were only 1.4 times. It can be noted that very large differences in the lateral mechanical migration rate of soil material were usually observed between the polar slopes.

TYPIFICATION OF SOIL CATENAS ON SLOPES

Based on the analysis of all the obtained data, we developed approaches to the typification of soil catenas on slopes from the manifestations of the soil material's mechanical migration (Table 4). It should be emphasized that this typification is of local significance and is not designed for use beyond the key plots. However, the methodological principles and diagnostic criteria behind this typification can be used for the development of similar classifications for other regions.

The typification is based on the introduction of three taxonomic levels. The first level is determined by the mechanical migration rate of the soil material. There are different approaches to the division of the soil erosion processes by the rates and volumes of the soil material removal. According to Shikula et al. [23], the soil erosion is considered low at soil loss rates <0.5 mm/year, medium at 0.5–1 mm/year, high at 1–2 mm/year, very high at 2–5 mm/year, and catastrophic at >5 mm/year. In the classification proposed by Zaslavskii [12], a soil loss rate below 0.5 t/ha per year is considered insignificant; 0.5–1 t/ha per year, low; 1–5 t/ha per year, medium; 5–10 t/ha per year, high; and, more than 10 t/ha per year, very high.

In the American classification, the gradation of the soil loss rates significantly differs from the above Russian approaches by higher rates of soil loss. For example, the soil loss tolerance values vary depending on the soil type from 2 t/A (or 5 t/ha) per year for a Typic Hapludalf to 6 t/A (or 15 t/ha) per year for a Typic Udorthent. The following average soil loss tolerance values are used for all the soils: <3 t/A (7.5 t/ha) per year, very low; 3–5 t/A (7.5–12.5 t/ha) per year, low;

Table 5. Typification of soil catenas on slopes of the studied key plots from soil erosion–accumulation manifestations

Soil material migration rate, t/ha per year	Soil material removed beyond catenas, %	Localization of accumulation zones			
		extra accumulation	upper accumulation	medium accumulation	low accumulation
<5 (hypodynamic)	>85 (extra open)				
	50–85 (open)		*IS*	TT	
	<50 (semi open)		*MC,* TA	*BY,* KG	**ME**
5–10 (mesodynamic)	>85 (extra open)	*IH*, **TT, IS, KG**			
	50–85 (open)		**KG**		
	<50 (semi open)				
>10 (hyperdynamic)	>85 (extra open)	BY, **TA, OG, IH**			
	50–85 (open)				
	<50 (semi open)				

Note: Soil catenas are denoted by roman type; catenas of undeveloped areas are denoted in italics; catenas on arable slopes of northern aspect are underlined; catenas on arable slopes of western aspect are denoted in thick print; catenas on arable slopes of southern aspect are denoted in underlined thick print. The survey plots are denoted in accordance with the indices from Table 1.

5–10 t/A (12.5–22.5 t/ha) per year, medium; 10–15 t/A (22.5–37.5 t/ha) per year, high; and >15 t/A (37.5 t/ha) per year, catastrophic.

In the system proposed by us, the soil catenas on slopes are subdivided into (A) hypodynamic catenas with soil loss rates below 5 t/ha per year, (B) mesodynamic catenas with migration rates of 5–10 t/ha per year, and (C) hyperdynamic catenas with migration rates >10 t/ha per year (Table 4).

The second level of typification is determined by the degree of openness of the soil catenas on slopes. The soil catenas are subdivided into (I) extra-open soil catenas on slopes, where the major part of the material (>85%) is removed beyond the catenas; (II) open catenas, where 50–85% of the material is removed beyond the catenas and the remaining material (15–50%) is accumulated within the soil catenas; and (III) semiopen catenas, where <50% of the material is removed beyond the catenas; i.e., the amount of material accumulated within the catenas exceeds that removed beyond them.

The identification of the third level is based on the localization of the accumulation zones of the soil material. The following subdivision is proposed: (1) extra-accumulation catenas containing no pronounced zones of soil material accumulation and (2) upper-, (3) medium-, and (4) low-accumulation catenas with the accumulation zones of the soil material in the upper, medium, and lower parts, respectively.

The proposed typification is based on the matrix principle, which excludes impossible catena types. In particular, the extra-accumulation catenas (1) can be only extra-open ones (I), because the other (open and semiopen) types of soil catenas on slopes imply the presence of intraslope accumulation zones of soil material. The extra-open catenas (I) contain only extra-accumulation catenas (1), because the major part of their soil material is removed beyond the soil catenas on slopes. Thus, the proposed typification based on the manifestation of the soil material loss–accumulation subdivides the soil catenas on slopes in the studied key plots into 21 types.

On the basis of the data obtained by the magnetic tracer method, we identified the studied soil catenas in accordance with the proposed typification (Table 5). The studied soil catenas of undeveloped areas are characterized by low mechanical migration rates of the soil material (no higher than 3 t/ha per year). The only exception is the forest-covered slope of the Hanover plot, which was presumably plowed in the past. The low mechanical migration rates of the soil material assign the studied catenas of virgin areas to the hypodynamic type (A). The portion of soil material accumulated within the virgin soil catenas on slopes was 35–100%. These high values of the intraslope accumulation of the soil material allow these catenas to be characterized as open (II) or semiopen (III) ones.

The developed soil catenas on the slopes of northern aspect are mainly of the hypodynamic type (A). Thus, the developed soil catenas on the slopes of northern aspect in the Tolmachi, Aleksandrovka, and Gracheva Loshchina plots and on the slope of western aspect in the Elektrougli plot were classified as hypodynamic ones.

The mesodynamic type (B) includes developed soil catenas on slopes of predominantly southern aspect. In particular, the soil catenas on the slopes of southern aspect in the Tolmachi, Springfield, and Gracheva Loshchina plots, as well as on the slope of western aspect in the Gracheva Loshchina plot, were classified among the mesodynamic ones.

The portion of the intraslope accumulation of soil material in the hypodynamic catenas (A) on the slopes of northern aspect was high; it made up 30–100% within the studied plots. Therefore, all the studied hypodynamic soil catenas on slopes (A) were characterized as open (II) or semiopen ones. At the same time, all the mesodynamic soil catenas (B) on the slopes of mainly southern aspect had a small portion of the intraslope accumulation of soil material (<15%) and were characterized as extra-open (I) or open (II) catenas.

The soil catenas on the plowed slopes of northern (the Yamskaya Step' plot) and southern (the Aleksandrovka, Zhdanovka, and Hanover plots) aspects were characterized as hyperdynamic catenas (C). It should be noted that all the studied hyperdynamic soil catenas are characterized only as extra-open (I) extra-accumulation (1) catenas. The portion of the intraslope accumulation of soil material in all the hyperdynamic catenas (C) was less than 5%.

On the basis of the proposed typification of the studied soil catenas on the slopes of the central East-European Plain and in the Mid-West of the United States, correlations were found between the localization of the zones of removal and accumulation of soil material and the morphology of the slopes. The studied hypo- (A) and mesodynamic (B) soil catenas on the concave–convex slopes of arable areas are of the extra- and upper-accumulation type; only the removal of soil material is observed in the lower convex part of these catenas. Hypo- (A) and mesodynamic (B) catenas with the concave profiles of the slopes show the possibility of material's accumulation in different parts of catenas. Hyperdynamic (C) soil catenas can be characterized as extra-accumulative ones, regardless of the slope profiles, because the removal of the soil material prevails in all parts of all these catenas.

CONCLUSIONS

The proposed typification allowed us to systemize soil catenas on slopes of the studied key plots in the center of the East European Plain and in the Mid-West of the United States in accordance with the features of the soil material removal–accumulation. On this basis, the relationships between the removal–accumulation rates of the soil material, the degree of openness of the soil catenas on slopes, and the localization of the zones of the soil material intraslope accumulation were quantitatively characterized. It was also revealed that the types of soil catenas on slopes identified during the systematization differ from each other in the migration features of the soil materials controlled by the land-use conditions and by the aspect and morphology of the longitudinal slope profiles. The proposed typification is oriented toward the studied key plots and is not designed for use beyond them. However, the methodological principles and diagnostic criteria behind this typification can be used in the development of similar classifications for other regions.

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