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SOIL EROSION

Soil Loss Tolerance of Brown Forest Soils of Northwestern Caucasus under Intensive Agriculture

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Abstract—The graded actions in substantiation soil erosion control measures in foothill agrolandscapes are discussed. Several approaches for the evaluation of soil loss tolerance were investigated. The values of this loss were used as normative indicators in the development of measures on soil erosion control.

The determination of soil loss tolerance is one of the most important scientific and applied problems in the development of soil control measures for agricultural lands. A number of methods for solving this problem are available [4, 6, 8, 10, 13]. Permissible erosion-induced losses of soil in agrolandscape are most often assessed on the basis of the velocity of natural soil formation. However, this assessment is discourteous, since the intensity of soil profile restoration is different for different soils and depends on the climate, vegetation, and the hydrological regime [2, 12, 14, 15].

Some foreign researchers also investigated the influence of other factors, namely, the reserves of the fertile soil layer, the decrease in yields, the contamination of water sources, and the expenses for soil erosion control measures.

The guidelines to assess the erosion-induced losses are practically undeveloped for brown forest soils, which occupy 1089 thousand ha in Krasnodar krai. For a solution to this problem, we took inventory of the long-term data on soils and climate in the foothill zone of this area (Krymsk–Goryachii klyuch–Severskaya station).

The research comprised the following activities: fertility of separate soil horizons was investigated [7], and their thickness and humus reserves were statistically assessed; critical and optimal depths of the humus horizon were determined. In addition, we evaluated the contribution of rain erosion (main type of water-induced erosion of soil in the Pre-Caucasus part of the Kuban' region) to soil loss tolerance for brown forest soils and developed a mathematical model of rain erosion.

Soil-geomorphic toposequences AB and CD (Fig. 1) were located on the slope of the southeastern aspect of the Abinskii experimental field. The slope averages 6° (10.6%) and the length of the water runoff line is 220–270 m. The forest, in which *Quercus robur*, *Pyrus communis*, and *Crataegus* predominate occupies the upper part of this slope and is about 50 m in length. The profile AB crosses the upper, middle, and bottom parts of the slope. The toposequence CD was located 40 m to the south of the toposequence AB on the 7° (in average) slope.

Automorphic conditions are characterized by a podzolized slightly unsaturated sandy loamy brown forest soil on deluvial heavy clay. As seen from the description of the soil profile, uneroded (standard) soil has the following horizon sequence: A1 + A1A2 + B1 + B2 + BC + C. The thickness of this profile reached 111 cm. The morphology of the brown forest soil under study was only slightly changed by water erosion and agricultural impact (slipping and tillage) because of geomorphic conditions and recent (since 1974) agricultural use of this land. This allowed us to reveal the quantitative correlation between the morphology of brown forest soil and crop productivity (Fig. 2).

In order to determine the optimal thickness of A1 + B1 + B2 horizons, we used (1) the "method of reconstruction of genetic horizons (based on "morphometric law of soil development" [11]) and (2) bioindication of soil conditions within the boundaries of the AB toposequence. The former method consists in finding a correlation between the thickness of a horizon and that of soil profile (A1 + B1 + B2). We found that the optimal thickness of the A1 + B1 + B2 horizons ranged from 60 to 65 cm. The result of the treatment of morphometric data showed that the correlation between thicknesses of the A1 + B1 + B2 horizon and the A + B1 horizon can be described by the following equation of regression: $A + B1 + B2 = 6.12(A + B1)^{0.62}$ (with the correlation coefficient = 0.81). According to these data, the optimal thickness of the humus horizon in brown forest soil ranges from 40 to 45 cm.

The critical thickness of humus horizons of brown forest soil was determined in special vegetation experiments.

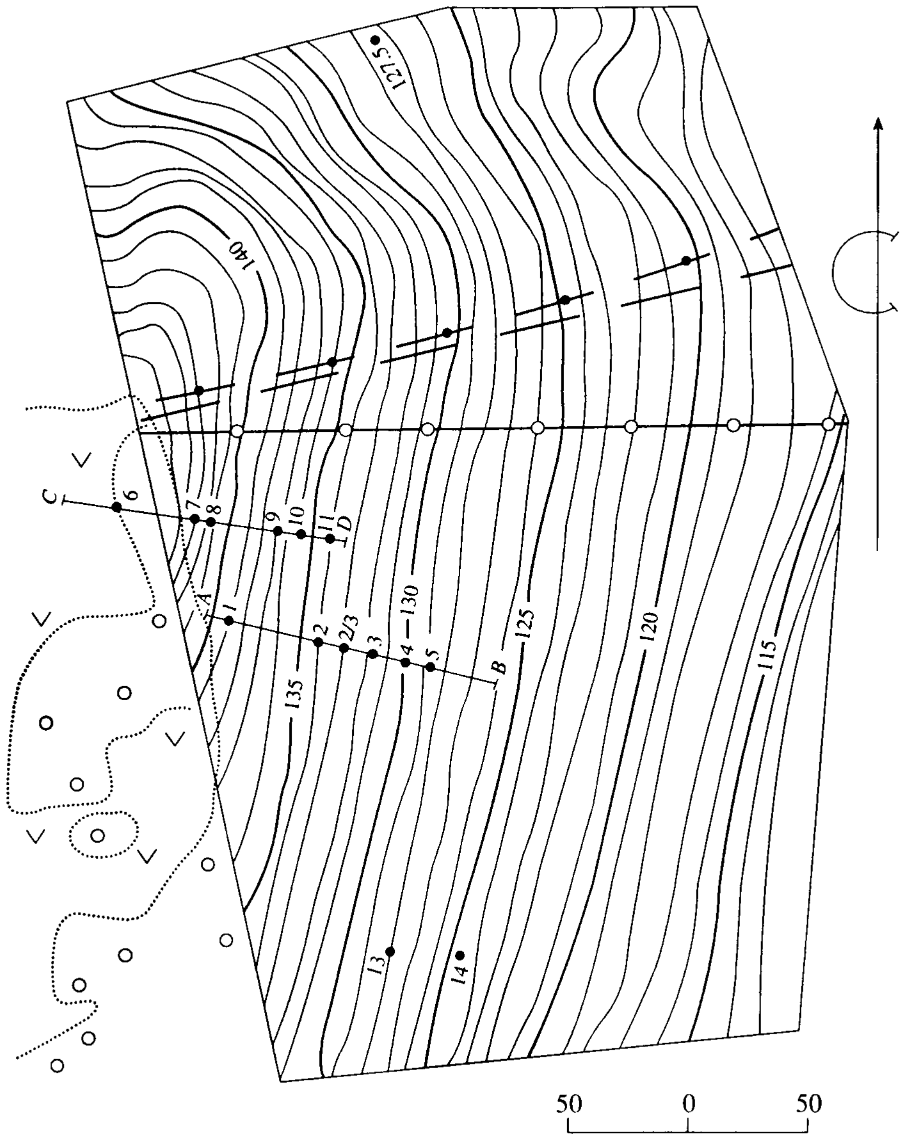

Fig. 1. Location of the soil profile on the Abinskoe experimental field.

Crop productivity is known to be an integral indicator of soil fertility. Therefore, method of analysis of data on crop yield obtained for soils with fixed participation of humus horizon [3] was used to determine a critical thickness of this horizon for main crops in field crop rotation of the foothill zone of this region. The investigations were conducted on soils displaying different degrees of erosion (in % of mass). The latter was determined on the basis of morphological criterion. The following variants were studied: (1) uneroded soils (100% of A horizon); (2) weakly eroded soils (80% of A horizon + 20% of B horizon); (3) moderately eroded (60% of A horizon + 40% of B horizon); (4) strongly eroded (40% of A horizon + 60% of B horizon); and (5) and (6) very strongly eroded soils (20% of A horizon + 80% of B horizon and 100% of B horizon, respectively). Since the relationship between the crop yield and the contribution of the A horizon of the modeled soil profile is nonlinear, logarithmic anamorphosis was used to determine a critical thickness of the humus horizon. It was found that this critical thickness for brown forest soil reached 16–17, 19, and 26 cm under cereals, tobacco, and corn, respectively.

The actual thickness of the humus horizon of brown forest soil was determined by the soil survey. Morphological and physicochemical properties of brown forest soils of different degrees of erosion were determined in 31 soil profiles. The statistics of the actual thickness of the humus horizons and humus reserves in them are represented in Table 1. On the basis of field and laboratory investigations, it was found that the profiles of slightly unsaturated and acid brown forest soils are composed of two main genetic horizons: the humus-accumulative A horizon and the textural B horizon with

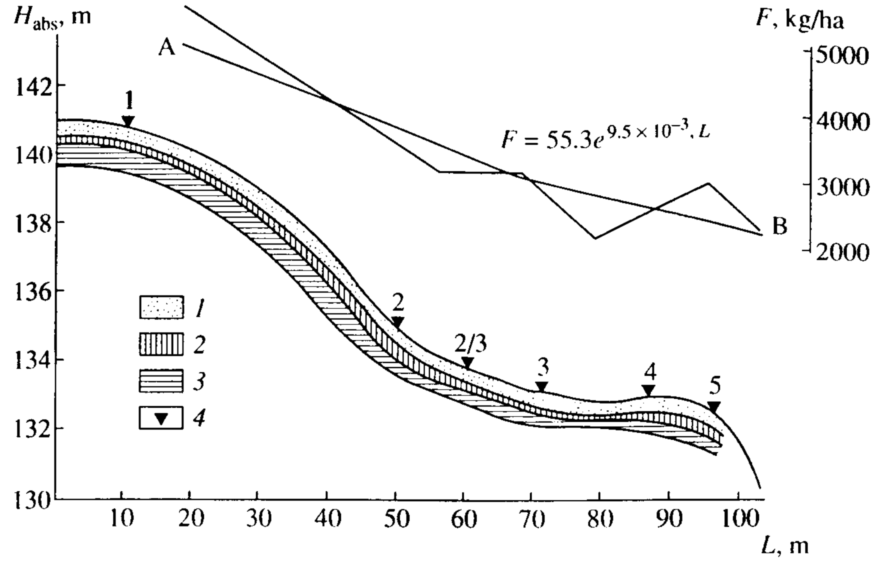

Fig. 2. Soil morphology and distributions of clover yield (*F*) and along soil–geomorphic toposequence AB. Horizons: (*1*) A1, (*2*) B1, and (*3*) B2; (*4*) soil profiles

intensive argillization. The transitional AB horizon comprises the lower part of the A horizon and the upper part of the B horizon. The total thickness of the A + AB horizon reaches 38 ± 1.4 cm.

The contribution of rain erosion to soil loss tolerance was determined with a rain simulator (Inst. of Agr. and Eros. Control) that yields rain intensity within the range of 0.3 to 2.0 mm/min. This investigation was conducted on the slope, with gradients from 2°–3° to 6°–7° (Table 2). Before rain erosion was calculated by the model, this model was adapted to the conditions under consideration. For this purpose, the following operations were performed: meteorological data for modeling rain erosion over a long-term period were collected; the model block that describes dynamics of soil moisture content over the same period was adapted; and the model was tested against results of rain simulation (Table 3). The database included only rains above 10 mm that fell during the April–October period for 25 years. The adaptation of the model block describing the dynamics of soil moisture meant the identification of the filtration and evaporation coefficients.

Table 1. Statistical characteristics of the actual thicknesses of genetic horizons of brown forest soil and of the humus content ($n = 31$)

Indicator	Statistics				
	X	σ	A	V	$X \pm t_{0.5}S_{\bar{x}}$
Thickness of horizon, cm					
A	31	3.5	–0.30	11	31 ± 1.3
AB	7	2.7	–0.15	38	7 ± 1.0
A + AB	38	3.8	–1.72	10	38 ± 1.4
Humus content in the horizon, %					
A	2.52	0.4	–0.02	15	2.52 ± 0.01
AB	0.65	0.08	–0.36	12	0.65 ± 0.03
Content of nitrogen in the horizon, %					
A	0.126	0.02	–0.02	15	0.126 ± 0.007
AB	0.032	0.004	0.55	13	0.032 ± 0.002

Note: n is the number of determination; X is the average value; σ is the standard deviation; A is the asymmetry; and V is the coefficient of variation.

Table 2. Conditions and results of rain simulation on the experimental plots

Variant	Slope gradient	Intensity of rain, mm/min	The number and quality of erosion losses	
			erosion, g/m^2 of abs dry soil	humus content in eroded soil, %
1	2–3	0.3	28.1	1.14
2		0.5	96.0	1.40
3	4–5	0.8	72.0	1.20
4		1.0	77.1	1.05
5	6–7	1.5	82.0	1.20
6		2.0	89.3	1.02

The permissible flow velocity v_{per} calculated by the Kuznetsov equation was taken equal to 0.045 m/s.

After adaptation, the model was used for the calculation of the long-term rain-induced soil losses on a given slope for a given soil treatment and crop rotation. The morphology of the slope was identified by a topographic map. The following soil-protective crop rotation was chosen on the plot under investigation: (1) corn; (2) winter wheat; (3)–(4) tobacco; (5) spring barley; (6) corn; and (7)–(9) perennial grasses (Table 4).

The error of determination of soil horizon thickness important for the assessment of the degree of erosion takes place for a number of reasons. According to the method described in works [2, 12], the soil loss tolerance for the time T should be less than the error of the humus horizon thickness determination. Thus, the following values are required for this calculation: (1) absolute error of the thickness (mm) determination and (2) time T (years) during which erosion rate 0.20–0.76 mm/year is permissible. Hence, the higher T, the lower the soil loss tolerance value. Table 5 represents the values of soil loss tolerance for weakly unsaturated brown forest soils for 20 years. In this case, we take the thickness of a standard soil equal to 600 mm, the precision of P determination equal to 5%, and the bulk density of the arable horizon equal to 1.10 g/cm^3. For each degree of erosion, the lower limit for the horizon thickness was taken. For example, for weakly eroded soil, $H = 0.75 \times 600 = 450$ mm. This means that the degree of soil erosion will remain unchanged for 20 years. Strongly eroded soils should be conserved.

Table 3. Mathematical modeling of rain erosion (method proposed by the Institute of Agriculture and Soil Erosion Control)

Distance, m	Slope gradients	Soil losses, t/ha per year	Layer of lost soil for 23 years, mm
0.0	0	0	0.0
3.0*	3.0	6.0	12.9
5.4		9.8	20.9
9.7*	11.0	14.3	30.5
10.8		16.1	34.3
15.5*	12.0	26.8	57.1
16.2		27.2	59.2
21.6		26.2	55.8
26.2*	7.6	25.4	54.1
27.0		25.6	54.5
32.4		28.0	59.6

Note: The value of bulk density for calculating the depth of eroded soil was taken to be equal to 1.10 g/cm^3.
*Distance to soil profile. The values of soil loss due to erosion for these distances were determined by interpolation with the use of cubic spline function.

The calculation of the soil loss tolerance was made according to the method developed in the United States [16] and improved in Ukraine [1]. This method requires the following input data: the minimal permissible thickness of humus horizon, which is determined in vegetation experiment for individual crops; the optimal soil depth, which is derived from soil and erosion surveys; rates of erosion-induced soil losses under main crops, determined by modeling. The advantage of this approach is that it allows one to take into account changes in soil quality knowing the humus budget in agroecosystems. In this case, we can solve the problem of maintaining keeping the equilibrium in soil humus status, so that the restoration of erosion-induced loss of humus horizon is possible during one rotation. According to [1], the model is written as follows:

$$Q_{set} = \left\{\frac{Q_h}{\Delta t}\left[1 + \sin\left(0.5\pi\frac{2h - h_1 - h_2}{h_2 - h_1}\right)\right] - \frac{Q_m}{\Delta t}\right\}\frac{10}{gpk},$$

where Q_{set} is soil loss tolerance, mm/year; Q_h is the humus store that forms for one rotation, t/ha; Δt is the duration of the crop rotation, years; h, h_1, and h_2 are the actual, maximal permissible, and optimal thicknesses of the humus horizon of soil, respectively. Q_m is the

Table 4. Soil erosion under corn (above line) and under winter wheat (under line), t/ha per year

Distance, m	Slope gradient				
	1	3	5	7	9
0	0	0	0	0	0
30	5.9/3.5	17.7/9.9	28.3/22.0	39.6/22.0	49.2/27.5
60	10.0/5.8	28.1/17.8	44.4/25.0	62.0/35.1	77.2/43.9
90	13.2/7.6	36.3/20.5	57.3/32.5	79.9/45.7	99.7/57.2
120	15.9/9.2	43.3/24.6	68.3/39.0	95.4/54.9	119.2/68.8
150	18.3/10.6	49.6/28.3	78.1/44.9	109.4/63.2	136.8/79.3
180	20.5/11.8	55.2/31.7	87.1/50.2	122.2/70.8	153.0/88.9
200	22.5/12.9	65.5/34.8	95.5/55.0	134.1/77.9	168.0/98.1

Table 5. Soil loss tolerance for weakly unsaturated loamy brown forest soil of the foothill part of Kuban

Degree of erosion	Loss of layer of soil standard, %	Soil loss tolerance (Q)	
		mm/year	t/ha per year
Uneroded	0–5	0.76	8.4
Weakly eroded	5–25	0.60	6.6
Moderately eroded	25–50	0.40	4.4

amount of humus mineralized for one rotation, t/ha; p is the bulk density of the upper (0- to 10-cm) layer of soil, t/m^3; g is the humus content in the arable layer, %; and k is the coefficient of increase of humus content in sediment runoff in comparison with that in soil.

Table 6 represents values calculated according to the American variant of the method [16], which mainly considers different sensitivities of crops in rotation to the thickness of fertile the soil layer. Since erosion-induced losses of soil in the district under study are considerable, soil erosion should be considered one of the most significant parameters in the determing the humus budget, which defines to a large extent the dependence of soil loss tolerance on actual erosion. The increase in soil loss tolerance in more eroded soils does not contradict the regularity of a more active restoration of the humus horizon in soils that were out of quasiequilibrium status owing to erosion [9].

The dependence of soil loss tolerance values on soil morphology along with the difference in erosion-control measures is the reason for adjusting the plants of crop rotation to the spatial pattern of thickness, the humus horizon or (in the general case) to soil units different in the degree of erosion. For this purpose, following soil erosion mapping, agroecological structurization of land should be conducted; i.e., rotation of crops should be matched to the peculiarities of soil.

CONCLUSIONS

The following conclusions were based on soil loss tolerance values obtained by two main methods.

(1) The annual permissible losses of a soil range from 4.4 to 6.6 t/ha, when calculated by a method presuming stability of the slope soil morphology for a time period with a certain intensity of erosion. When rates of optimal and critical thicknesses are taken into account in addition to the actual thickness of the humus horizon, the annual erosion-induced losses of brown forest soil can reach 0.85 to 2.3 t/ha under tobacco, 0.64 to 1.7 t/ha under intertilled crops, and 0.2 to 0.8 t/ha under perennial grasses (Table 6). These rates may be considered the soil loss tolerance compensated by the natural soil formation and, hence, allow long-term use of brown forest soil in agrolandscape.

(2) According to calculations presuming the simple compensation of humus reserves in brown forest soil, the annual permissible losses of soil can range from 3.5

Table 6. The calculated values of soil loss tolerance for brown forest soils of Krasnodar krai, t/ha

Slope gradient, deg	Intertilled and industrial crops			Tobacco			Winter and spring cereals			Perennial grasses (3 years and above)		
	Degree of erosion/length of slope, m*											
	1/125	2/202	3/131	1/125	2/202	3/131	1/125	2/202	3/131	1/125	2/202	3/131
2–4	0.64	–	–	0.84	–	–	0.88	–	–	0.21	–	–
4–6	–	1.45	–	–	1.96	–	–	2.02	–	–	0.30	–
6–8	–	–	1.70	–	–	2.29	–	–	2.38	–	–	0.78

Note: Hyphen implies that crop is absent.

*The number of 1, 2, and 3 denote uneroded, weakly eroded, and moderately eroded soils, respectively.

to 4.6 t/ha for cereals and from 4.3 to 6.6 t/ha for intertilled crops.

We can recommend the following order of procedures to determine soil loss tolerance:

(1) Generalization and statistical treatment of hydrometeorological data and genetic characteristics of soil for the chosen model of the water–erosion process as well as chemical analysis of sediment runoff and determination of erosion-resistant properties of soil by rain simulation. Calculation of the rate of erosion for typical combinations, including geomorphic and soil conditions and groups of crops (grouping was made on the basis of their soil protective efficiency).

(2) Determination of the optimal thickness of the humus horizon of soil with the use of soil–geomorphic erosion catenas and periodical testing.

(3) Performance of vegetation experiments for determining the critical thickness of the humus horizon for main groups of zoned crops. This grouping is made on the basis of the structure of the root system and the ability of crops to adapt to concrete soil conditions.

(4) Evaluation of the velocity of natural soil formation in the automorphic conditions on the basis of field soil-chronological investigation of objects, whose age is determined by archaeological method and corresponds to the main periods of the Holocene.

(5) Collection of data for evaluating the humus budget of soil.

(6) The justification of a two-step system of soil loss (tolerance): for the final runoff accumulation sites on fields under crop rotation and for the catchment as a whole.

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