ISSN 1064-2293, Eurasian Soil Science, 2018, Vol. 51, No. 2, pp. 221–228. © Pleiades Publishing, Ltd., 2018.
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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Factors of the Development of Water Erosion in the Zone of Recreation Activity in the Ol'khon Region

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Received September 2, 2016

Abstract—Specific features of water erosion of thin soils under conditions of nonpercolative water regime and intense recreational loads were studied in the Ol'khon region (Irkutsk oblast). An experiment on the transfer of terrigenous particles under the impact of rainfall simulation was performed. A thorough description of landscape characteristics affecting water erosion development was made. As a result, a multiple regression equation linking the transported matter with the slope steepness, projective cover of vegetation, the degree of vegetation degradation, and the fine sand content in the upper soil horizon was developed; the multiple correlation coefficient R reached 0.86. On this basis, the map of water erosion assessment for the study area was compiled with the use of landscape and topographic maps. The maximum intensity of water erosion is typical of the anthropogenically transformed landscapes on steep slopes with the low vegetative cover on the mountainous noncalcareous steppe soils and on thin loamy sandy surface-gravelly chestnut-like soils.

Keywords: linear regression model, experiments, recreation load, Lithic Leptosols

DOI: 10.1134/S1064229318020151

INTRODUCTION

The Ol'khon region is found in the central part of the large Cis-Baikal region. It represents a unique natural complex of steppe and forest-steppe landscapes. Active development of this territory in the recent decades has led to aggravation of land use conflicts related to the multifunctional use of lands (nature preservation, residential, agricultural, and recreational). Scientific knowledge is required to fine optimum land uses. At present, local landscapes mostly suffer from the unauthorized recreational activity.

Recreational potential of the Ol'khon region is specified by a relatively favorable climate combined with an exceptional landscape diversity (from dry steppes to mountainous tundra), fascinating panoramic views, flora and fauna diversity, hydromineral resources, and high air quality. Unique natural monuments and the presence of rare and endangered species of plants and animals attract visitors; this is one of the most attractive regions in Irkutsk oblast. According to the administration of the Ol'khon region, there are about 100 recreation centers on its territory; in summers, about 20 children's health camps work on the coast of Lake Baikal. Approximately half a million people visit the region in summer. Thus, in 2014, it was officially visited by 542600 people; a considerable part of the visitors preferred the nonorganized type of recreation [21].

The growth of tourist loads affects coastal landscapes and leads to the appearance of a dense network of illegal dirt roads. The area under buildings rapidly increases. Thus, in the recent decade, on the study area (19.86 km^2 in area), buildings have been constructed on 1.25 km^2 (6.3% of the study area). At the same time, the impact of the uncontrolled cattle grazing on the local ecosystems has decreased. The number of cattle increased from the beginning of the 20th century to the 1970s; the maximum livestock population was in 1970 (60000 heads); then, it began to decrease. In 2003, the livestock population was 15900 heads; in 2012, it was as low as 8279 heads [20, 26].

The soils of the investigated territory are characterized by the coarse texture of the upper horizons, thin gravelly profiles, weak leaching (disperse carbonates occur at the depth of 10–40 cm), the presence of the films of iron hydroxides, silica, and carbonates on rock fragments of different chemical compositions, considerable variability in the humus content upon a narrow range of textural changes, and the virtual absence of soluble salts and carbonate and gypsum concretions. Most of the soils are developed under the nonpercolative type of soil water regime. Diverse geological, geomorphic, and climatic conditions specify spatial differentiation of the soil cover [16, 17, 19].

The climate and water regime of the soils favor the development of erosional processes. The latter are

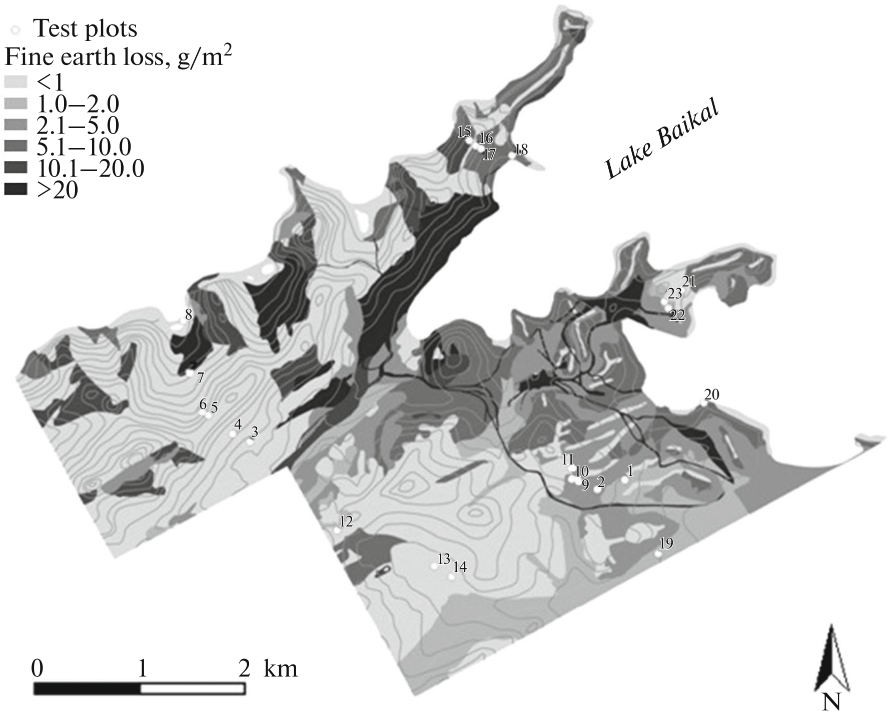

Fig. 1. Extrapolated values of the experimentally measured loss of fine earth in the study area.

enhanced under the impact of high recreation loads. In turn, water erosion of the soils disturbs the water-protective function of geosystems in the basin of Lake Baikal. In this context, the determination of the intensity of water erosion in dependence on the particular landscape characteristics is important for the choice of appropriate nature protection activities.

According to the experiments of B.P. Agafonov, the discharge of mineral and organic matter in Lake Baikal sharply increases during rainstorms. During six years of special observations, the maximum discharge was related to heavy rains in July 1971; the amount of terrigenous material washed off into Lake Baikal during this period exceeded the mean annual discharge by 2.2 times. During heavy rainstorms, sand fractions are transported by water flows. On gentle slopes and subhorizontal surfaces in the steppe zone, the fine sand fraction (0.1–0.25 mm) is mainly washed off [2].

The aim of our study was to determine the intensity of transportation of terrigenous material with runoff flows caused by heavy rains upon the increasing recreation loads in the region.

OBJECTS AND METHODS

A study area with steppe and forest-steppe ecosystems in the Ol'khon region was selected for this study. Steppes are characterized by the high rates of exogenous processes that are amenable to instrumental measurements [12]. The major factors that affect the lithodynamic processes are the intensity of weathering of parent materials and the water and wind erosion [2]. Atmospheric precipitation induces sheet erosion in the areas poorly protected by the vegetative cover; splash and rill erosion are developed.

The Kurkut study area is found in the northern part of the Ol'khon Plateau, on the southeastern coast of the Mukhor Gulf in Ol'khon administrative district of Irkutsk oblast. It belongs to the central part of Cis-Baikal region, within the boundaries of the Pribaikalskii National Park, where economic activities should be regulated in accordance with the requirements for the preservation and improvement of the water-ecological situation and the self-purification potential of landscapes [26].

Steppe communities are widespread in the study area. Herbaceous grassy and herbaceous wormwood steppes with a predominance of *Festuca lenensis* Drobow., *Stipa* spp., and *Chamaerhodos altaica* (Laxm.) Bunge form relatively dense sod horizons. Forest-forest communities are represented by herbaceous grassy larch woodlands. Meadow-bog communities occupy less than 1% of the key plot area and occur in the depressions of the coastal zone of Lake Baikal. In places of tourists' camps, plant communities composed of *Carex duriuscula* C.A. Meyer, *Artemisia frigida* Willd., *Potentilla* spp., and *Plantago* spp. with long roots are developed. These species do not form dense sod layers on the surface.

Steppe conditions of the territory allow cars to move without roads in different directions, even upslope the mountains to their tops. As a result, the network of disturbed areas with scarce vegetation, compacted and eroded soils, and deep (up to 1 m) hollows is formed on the slopes. Soil erosion occurs on the slopes due to the anthropogenic impact. Often, surface rills are deepened to the depth of the layer compacted by the wheels. Excessive recreational loads on the territory cause the damage of vegetation up to its complete destruction.

Though the annual precipitation in the study area is minimal for the basin of Lake Baikal (200–300 mm), the danger of water erosion is high, because a larger part of the annual precipitation is represented by heavy summer rains [23]. According to records of the Khuzhir weather station, in summer 2015, rainstorms occurred 61 times (rp5.ru website). Under conditions of sparse steppe vegetation transformed under the impact of a recreational activities [22] and the dense network of illegal dirt roads, the danger of strong water erosion considerably increases.

The landscape GIS of the study area was created on the basis of digitized and georeferenced large-scale (1 : 25000) landscape map by Zagorskaya [10] updated with due account for the new recreational infrastructure facilities seen on the satellite images [30]. The map contains information on the topography, soils, and vegetation in each of the landscape polygons. This map was used for planning the experiments and for extrapolation of their results.

To determine characteristics of the water erosion in dependence of the particular landscape conditions, the amount of terrigenous material transported by surface water flows was measured on 23 test plots in August 2015 (overall, 28 measurements were made, Table 1). The coordinates of the test plots of 10 × 10 m were determined, and the characteristics of their topography and land cover (percent of barren surface, coarse tree litter, ground litter, and vegetative cover) and floristic composition of the plants were thoroughly described. Aboveground and underground phytomass of herbs (air-dry weight) was determined, and soil samples from the major genetic horizons were taken. In laboratory, particle-size distribution was analyzed using the Kachinskii method. Bulk density of the soil was determined with cutting rings (100 cm^3) in three replicates; for the stony soils, the method suggested by Zaidel'man was used in two replicates. The organic carbon content was determined by Tyurin's method [5, 6, 14].

There are many studies devoted to experimental modeling of water erosion and surface runoff; runoff simulation is often applied [9, 27–29]. Taking into account this experience, we developed a mobile device simulating heavy rains and making it possible to catch fine earth transported by surface flows (Fig. 2).

Fig. 2. Rainfall simulation device applied in the study.

On each of the plots (0.25 m^2), 3 L of water (25% of the mean July precipitation according to the Elantsy weather station data) is evenly poured over the surface within 10 min. The mean water drop size is 2 mm, the height of the drop fall is 0.5 m, and the artificial rainfall intensity is 1.2 mm/min. The fine earth transported by water flows on the surface is trapped and weighed after drying. The trap is a filter that passes water and captures solid particles. The removable multilayer filter is placed at the base of the device and is attached to the underlying surface of the test area. A more detailed description of the device is given earlier [30].

Measurements were conducted for slope areas in different types of landscapes. On some of the test plots, measurements were performed twice in different loci characterizing the general state of the plot (e.g., plot 17.1) and the state of the plot in the area of maximum anthropogenic load (e.g., on the spontaneously formed dirt road, plot 17.2). The degree of degradation of plant communities was estimated in conventional grades (1—undisturbed vegetation, 5—severely disturbed vegetation) [22]. These estimates took into account the degree of trampling and mechanical damage to vegetation, its species composition, the portion of the trail network, surface littering, and the presence of fireplaces.

RESULTS

Information on the landscape characteristics of the territory and quantitative estimates of parameters

Table 1. Characteristics of test plots

Point no.	Slope steepness, degrees	Vegetative cover, %	Degradation stage	Sand content in the upper horizon, %	Aboveground phytomass of herbs, g/m^2	C_{org}, %	Fraction >1 mm, %	Fine earth loss, g/m^2
1	1.8	30	3	23.58	161.6	4.80	5.3	1.3
2	6.3	20	3	24.17	169.2	3.59	5.2	3.5
3	5.2	20	3	23.16	228.6	2.33	20.5	0.1
4	11.1	10	2	74.36	94.8	3.08	57.7	0.8
5	23.4	20	1	69.95	127.2	8.52	23.1	0.4
6	17.8	10	1	76.23	58	5.99	13.3	0.6
7.1	13.9	0.01	5	61.83	0	3.29	49.3	33.2
7.2	10.8	10	4	52.71	90.9	–	–	26.8
8	1.0	100	1	40.20	322.1	6.12	–	0
9.1	3.7	15	3	45.15	87	4.43	22.6	1.9
9.2	5.4	0.01	5	53.36	0	–	–	7.8
10.1	5.1	20	3	64.33	128.4	3.71	5.8	0.1
10.2	7.2	0.01	5	67.72	0	–	–	52.4
11	14.9	10	2	0.20	189.5	4.20	–	0.4
12	7.7	25	2	24.36	63.9	7.83	42.6	0.4
13	1.0	15	4	9.54	25.8	10.98	8.8	0
14	1.0	90	4	43.15	138.5	12.52	–	0
15	12.2	15	3	37.45	54.3	5.03	67.7	0.4
16	16.9	40	4	39.40	35.8	7.40	53.1	0.4
17.1	6.1	10	4	27.45	110.9	3.75	48.6	5.1
17.2	5.9	0.01	5	0.20	0	–	–	9.9
18	1.0	60	4	38.92	124	3.31	–	0
19	3.2	10	5	59.68	63.6	9.10	7.1	2
20	10.3	20	4	57.39	101	4.50	73.9	8.2
21	14.2	10	3	43.68	146	7.50	11.6	0.4
22	16.2	10	4	50.21	146	3.90	27.2	0.4
23.1	7.9	30	4	34.50	72.3	3.50	–	1.5
23.2	7.1	0.01	5	69.69	0	–	–	27.8

Dashes stand for “Not determined”.

affecting the intensity of water erosion were obtained during the fieldwork.

The soil cover of the investigated territory is discontinuous and fragmentary. The formation of fully developed soil profiles on steep slopes with gravelly substrates is retarded.

Soils that develop on the outcrops of massive crystalline bedrocks under the layer of foliose and crustose lichens are classified as typical humus petrozems (W-R) (Lithic Leptosols (Humic)). Soils of hollows on the slopes of northern aspect are developed from a thin layer of fine earth and gravels underlain by the hard bedrock at a shallow (<30 cm) depth; these are light-humus lithozems (AJ-C-R) (Lithic Leptosols). In the forest-steppe zone on the southeastern slopes, gray-humus (soddy) soils (AY-C) on bedrock detritus are formed (Dystric Hyperskeletic Leptosols). Light-humus soils (AJ-C) (Eutric Leptosols) are formed on the southeastern slope of the Primorskii Ridge under sparse steppe vegetation; often, the soil surface is covered by a thin sand layer [15].

The content of gravels (>1 mm) and coarser rock fragments greatly affects the properties of soils, especially thin not fully developed soils. The presence of skeletal material worsens the physical properties of soils; in particular, the soil water-holding capacity decreases. Skeletal (stony) soils are characterized by the low supply of nutrients.

The studied soils have a loamy sandy or light loamy texture with a predominance of fine sand fraction. The

Table 2. Regression parameters

Variable	Coefficient	Standard error	Student's *t*-test	Significance level
X_1	1.122036193	0.287686	3.900214	0.000721
X_2	–0.273956132	0.099523	–2.75271	0.011334
X_3	1.55271259	0.583324	2.661838	0.013932
X_4	0.353287315	0.126104	2.801549	0.010134

X_1—natural logarithm of the slope steepness (degrees), X_2—natural logarithm of the vegetative cover (%), X_3—natural logarithm of the degree of degradation of vegetation (grade), and X_4—natural logarithm of the fine sand content in the upper soil horizon (%).

high content of coarse silt and fine sand particles in the upper horizon does not favor its aggregation. The water stability of the aggregates is low; they break down under the impact of several rain drops. The presence of an aquiclude at a shallow depth contributes to the high soil erodibility. Snowmelt and rainstorm erosion are common; erosional processes are accompanied by some sorting of the disaggregated material in the upper horizon [11].

In order to determine the major factors of the erosional transport of soil material, we used the results of 28 experimental determinations of the soil washing off by simulated rain. The following parameters were analyzed together with these data: slope steepness, slope aspect, bulk density of the soil (g/cm^3), the degree of vegetation degradation, vegetative cover of the surface, the contents of soil particle-size fractions (coarse sand (1–0.25 mm), fine sand (0.25–0.05 mm), coarse silt (0.05–0.01 mm), medium silt (0.01–0.005 mm), fine silt (0.005–0.001 mm), and clay (<0.001 mm), the content of gravels and stone fragments, and the organic carbon content (%). Their factual values were normalized via division be the maximum value to obtain dimensionless parameters. For further processing, their logarithms were taken, because the logarithmic scale allows one to smooth the asymmetry of data distribution (within the wide range of variation). This scale is considered to be adequate for the description of natural relationships [25]. Then, the step-by-step regression analysis was performed. The parameters characterized by the high correlation coefficient of pair regression and the parameters that did not affect the correlation coefficient were excluded from the analyzed sample. Thus, the pair correlation was high for the measured above- and underground phytomass ($R = 0.99$), the vegetative cover and the aboveground phytomass of herbs ($R = 0.97$), the contents of coarse and fine sand ($R = 0.79$), and the contents of coarse and medium silt ($R = 0.83$). The linear multiple regression equation with the highest multiple correlation coefficient ($R = 0.86$; $R^2 = 0.74$; the corrected multiple determination index 0.69) takes into account the following factors: X_1—natural logarithm of the slope steepness, X_2—natural logarithm of the vegetative cover, X_3—natural logarithm of the degree of degradation of vegetation, and X_4—natural logarithm of the find sand content in the upper horizon.

The multiple linear regression equation (the actual value of F-test is 16.07; the actual Student's *t*-test of the correlation coefficient significance is 6.49, Table 2) is as follows:

$$Y = 1.12\,X_1 - 0.27X_2 + 1.55\,X_3 + 0.35\,X_4 + 4.54,$$

where Y is the natural logarithm of the amount of transported fine earth.

To verify the model, the relationship between the fine earth transportation values calculated by the equation and determined in the field (on a logarithmic scale) was considered (Fig. 3). In some cases, the calculated values were two–three times higher than the empirical values (for example, for points 3, 9.2, 10.1, and 15); in other cases, they underestimated experimental results by three of more times (for points 1,2, 7.2, 17.1, and 17.2). In this context, it is interesting to consider the plots established in the heavily disturbed loci (dirt roads) and on the "conventional background" (e.g., points 7.1 and 7.2, 9.1 and 9.2, 17.1 and 17.2). It can be seen that the model overestimates the values for cases with the degraded vegetation and vegetative cover close to zero with other parameters (slope steepness and the content of sand in the upper soil horizon) being similar. For background areas with less disturbed vegetation, the calculated values are lower than the experimental values.

According to the equation, the soil washing off is mainly affected by the degree of vegetation disturbance (related to recreational loads) and the slope steepness; the vegetative cover and the content of fine sand in the upper horizon are the next in importance.

The results of experimental measurements of the fine earth transportation by rainfall-induced surface flows attest to its significant variability (0.01–52.4 g/m^2 per 10 min of simulated rainfall). The maximum values correspond to the anthropogenically transformed territories (fourth and fifth degradation stages) with the low vegetative cover (0–20%) and with slopes of 7° and more.

In this case, vegetation plays a regulating role. In the case of recreational loads, it suffers negative impact. The aboveground phytomass of herbaceous steppe and meadow vegetation measured on the test

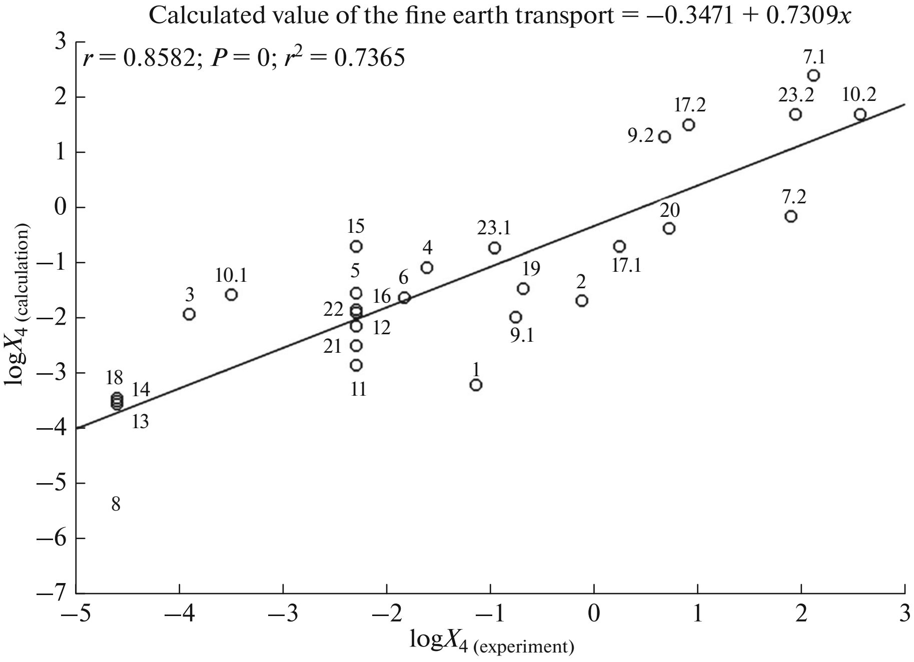

Fig. 3. Calculated versus experimentally measured values of the fine earth transport.

plots is generally low and varies from 25.8 to 322 g/m^2. In the zones of dirt roads and tent camps, the vegetation is practically absent, and the aboveground phytomass tends to zero. The minimum values correspond to the points with the high degree of vegetation degradation; thus, in residential areas, the aboveground phytomass is about 40–44 g/m^2 [30].

The obtained data were included in the GIS as attribute characteristics of landscape units distinguished on the investigated plot. This made it possible to extrapolate the results of experimental observations of soil loss with due account for the particular characteristics of each landscape, slope steepness, and the degree of degradation of the plant cover. These data were taken into account in the map of erosion intensity assessment.

DISCUSSION

There are dozens of water erosion models developed in various countries, and their number continues to increase. Models accounting for the vegetation cover, topography, and soil properties are usually applied.

In the universal soil loss equation (USLE and RUSLE models), direct proportionality is assumed between the average annual soil loss and the mean annual rainfall erosivity index obtained via summation of the total kinetic energy and maximum 30-min intensity of individual rainfall events. However, as noted by Hudson [7], even rare extreme rainstorms are of exceptional erosive efficiency. An analysis of the 10pyear observation series at the runoff sites in Missouri showed that during this period, eight maximum runoff-forming heavy rains gave 88% of the total soil loss [1]. The impact of extreme heavy rains should be even more manifested in the agricultural regions of Russia with a greater climate continentality. In conditions of different natural zones of the European part of Russia, incidents of soil loss of high intensity (tens and hundreds of tons per hectare) from slopes under fallow lands and tilled crops were recorded [4]. The mean annual soil loss according to observations on runoff sites (with short series of observations) comprised several tons per hectare, or was totally absent [8, 18].

Both of the problems—the assessment of the erosive potential with due account for the soil permeability and its assessment for single heavy rains—may only be solved within the framework of deterministic physically based models, such the WEPP model [24]. However, time is needed for them to be implemented in Russia.

It is necessary to develop or adapt the already existing water erosion mathematical models to the natural and economic conditions of the study area for solving the problems of management of agrolandscape systems. In this regard, the improvement of existing models should be aimed at actualizing the hydrometeorological factors of heavy rains and spring (snowmelt) runoff taking into account the soil permeability; changes in the soil erodibility upon continuous degradation of the soil cover should also be taken into account.

The investigated landscapes in the Ol'khon region differ from those in the reference area in the United

States in their soil and climatic conditions. The differences in water permeability and soil moistening conditions are extremely high. Thus, the soil thickness on the investigated territory rarely exceeds 50 cm, and heavy rains predominate in the annual precipitation. These factors do not allow us to use universal equations for the soil loss assessment.

Despite the fact that the rainfall erosivity index for the investigated study area is minimal at the territory of Siberia [3], other factors affect the active development of water erosion. As a rule, the amount of soil transported with runoff flows reaches 50–100 g/m^2 per year [13].

The anthropogenic impact considerably increases the intensity of natural erosion because of the slope steepness, high stoniness of the soil, sparse vegetation, and thin poorly developed soil profiles.

CONCLUSIONS

Landscapes differ in their tolerance toward water erosion processes and anthropogenic impacts. The following natural complexes are characterized by the high soil loss: light-humus lithozems (Lithic Leptosols) with bedrock outcrops under steppe communities with caragana and wormwood (in some cases, with the presence of sparse larch trees), light-humus soils (Eutric Leptosols) under feather grass–wheatgrass–herbaceous vegetation, and light-humus lithozems (Lithic Leptosols) with outcrops of gneiss and amphibolite bedrocks under the forb–grassy steppes with caragana.

The obtained model of the dependence of soil loss on the landscape factors takes into account the natural specificity of the investigated territory and the recreational loads on it and can be applied for the calculation of soil erosion in the Ol'khon steppes in general.

ACKNOWLEDGMENTS

This study was performed within the framework of research work of the Sochava Institute of Geography (Siberian Branch of the Russian Academy of Sciences) (project nos. IX.127.2 and IX.137.3) and partially supported by the Russian Foundation for Basic Research (project no. 17-05-00588) and the Russian Geographical Society (project no. 17-05-41020, contract no. 02/2017).

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Translated by D. Konyushkov