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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Effect of Irrigation-Induced Erosion on the Degradation of Soils in River Valleys of the Alpine Pamir

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1 **Abstract**—Results of a study were analzyed, which was conducted on the arable stony alpine soils in the Gunta River valley and the upper Panj River. Such soils are occurring in different regions of the Western Pamirs. The physicochemical properties of the soils were studied using conventional methods, and the degradation rate of the soil cover was determined using the radiocesium method. Low contents of humus (<2.5%) and 2 nutrients, primarily related to the natural pedogenesis conditions, were indentified for the subsoils of the studied river valleys. The limiting factors are temperature and precipitation. The irrigation-induced erosion, which is manifested on slopes of >2–3° with furrow irrigation, is the main anthropogenic factor of soil degradation. The lower content of humus in the soils of the Panj River valley is due to the larger portion of slopes >3° with furrows irrigation, on which also maximum rates of irrigation-induced erosion (>30 ha/year) were observed.

Keywords: alpine soils, Western Pamir, ^{137}Cs, degradation, irrigation-induced erosion

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INTRODUCTION

Attention to the study of soils on high-altitude areas has increased in recent decades because of their special sensitivity to the climatic changes most manifested in the mountain zone above 2500 m. The main attention is drawn to the problems of pedogenesis and soil classification [6, 7, 16, 17]. At the same time, the high-mountain soils, especially those developed on river valley floors, are actively used in agriculture and form the basis for the production of food for the local population and forage for domestic animals. Therefore, it is of great importance to assess the effect of the long-term agricultural use on the fertility of alpine soils. The Pamirs are one of these regions. The Pamir mountains occupy almost half of the area of Tajikistan: 25700 km^2. However, only 240 km^2 of it (or less than 1%) is occupied by arable lands. Almost all the arable lands are located in the bottoms of river valleys in the altitude belt of 1700–3500 m asl, and only an insignificant part of them occur on the valley sides, predominantly terraces of glaciofluvial and glaciolacustrine origin. In most valleys, agricultural production began no more than 200 years ago. An exception is provided by the Ishkashim district located in the very south, where the Panj River bottom was developed already 2100–2300 years ago. The alpine belt occurring above 2600 m, where the major part of the arable land is irrigated during the short droughty summer (because crop cultivation is possible only under regular irrigation), is the most dependent on climatic changes. The changes of the soil properties on the arable lands in the alpine belt of Pamir have been almost unstudied during the past 40 years. Most pasture lands occur on the steep slopes of mountain ranges, where shallow stony soils strongly degraded due to overgrazing are predominant.

The aim of this study was to assess the current state and degradation rate during the past 50 years of the cultivated soils in two regions of the alpine Pamirs.

CLIMATE IN THE PAMIRS AS THE LIMITING FACTOR OF PEDOGENESIS

The Pamirs are located in the eastern part of the zone with a Mediterranean climate of the Eurasian continent, which is spreading from the west to the east. The climate is formed under the effect of warm and humid western air masses and cold dry northeastern Siberian anticyclones. The orography and altitude of the country, which determine the local circulation of air masses, significantly affect the climate. The Pamirs largely belong to the area with an arid climate. The aridization of the climate and the development of a

Table 1. The main climatic parameters of Western Pamir [20, 21]

Meteorological stations	Altitude, m	Mean annual air temperature	Mean t° of the period with positive mean monthly temperatures;	Sum of $\frac{t > 10°}{t > 5°}$	Sum of $\frac{t > 10°}{t > 5°}$ per 1° of the mean warm-period temperature	Annual precipitation, mm	Mean annual air humidity, %	Mean frostless-period duration
Humragi	1737	12.1	16.5	$\frac{4140}{4449}$	$\frac{251}{270}$	238	44	247
Rokharv (Vanch)	1751	9.9	14.4	$\frac{3562}{3862}$	$\frac{247}{268}$	232	53	207
Poimazor	2420	–	–	–	–	610	–	–
Rushan	1981	9.6	14.0	$\frac{3458}{3763}$	$\frac{147}{269}$	262	46	203
Khorog	2075	7.7	13.5	$\frac{3377}{3665}$	$\frac{250}{271}$	257	48	206
Sharipdara	2300	–	–	–	–	286	–	–
Chartym	3157	–	–	–	–	231	–	–
Ishkashim	2524	6.9	11.3	$\frac{2709}{3022}$	$\frac{240}{267}$	119	43	177
Jaushangoz	3410	–2.0	7.6	$\frac{805}{1310}$	$\frac{106}{172}$	177	51	30

continental climate in the Pamirs began in the middle Pleistocene. This is confirmed by the palynological studies of interglacial lacustrine deposits [18]. In the bottom bench of these deposits, which Vasil'ev dates to the middle Pleistocene [5], a significant amount of woody pollen was found with a predominance of coniferous (Cedrus, Pinus, and Picea) pollen. However, in the top bench, the amount of woody pollen significantly decreases, and the portion of herbaceous plants increases, respectively. The beginning of the climate aridization in the middle Pleistocene was due to the elevation of the mountain systems from the south (Hindu Kush and Karakorum), which formed a barrier for the penetration of the Indian monsoon. During this time period, the Pamirs were lifted by 2–2.5 km [24].

The climatic conditions play an essential role in both the pedogenesis and agricultural land use on a specific area. In the Pamirs, the precipitation, the mean annual air temperature, and the sum of the effective temperatures vary in wide ranges [20, 21] (Table 1). The mean annual temperature decreases with the altitude from 12.1 to –1.0°C, and the mean temperature of the warm period decreases from 16.5 to 7.6°C. This indicates that cereal crops (mainly for green mass) can be grown at altitudes up to 3400 m, where the sum of the active temperatures >5°C is 1310°C. However, the duration of the frost-free period abruptly decreases to 30 days at these altitudes. The Pamirs are surrounded from all sides by other mountains, which hamper the penetration of humid air masses. The most significant precipitation is noted in northwestern Pamir; it gradually decreases when going to the southeast. A direct correlation between the altitude of the area and the total annual precipitation is observed for some Pamir regions provided with long-term meteorological data. These regions include northwestern Pamir; the Panj River valley between Khorog and Kalaikum, where the river flows strictly from South to North; and the area of the Panj right tributaries flowing from east to west and entering the Panj in this area. The maximum precipitation is noted in the heads of these valleys, where it is almost double that observed in the lower courses of the tributaries [21]. On the rest of the Pamir area, the precipitation is less dependent on the altitude of the country and is mainly controlled by the orography. For example, the precipitation in the Ishkashim district located in the South of the Pamirs is 5 times small than that in the Poimazor district located at the same altitudes in the North of the Pamirs. The mean annual precipitation is usually within the range of 231–262 mm. The precipitation predominantly falls during the winter–spring period (80% of the total). One rainfall of >20 mm usually falls in Khorog annually, while one rainfall of 10 mm with a maximum rate of <0.1 mm/min falls annually in the Ishkashim area in the very South of the Gorno–Badakhshan Autonomous Region (GBAR) [21]. Therefore, neither snowmelt nor erosion due to rainstorms is observed in the

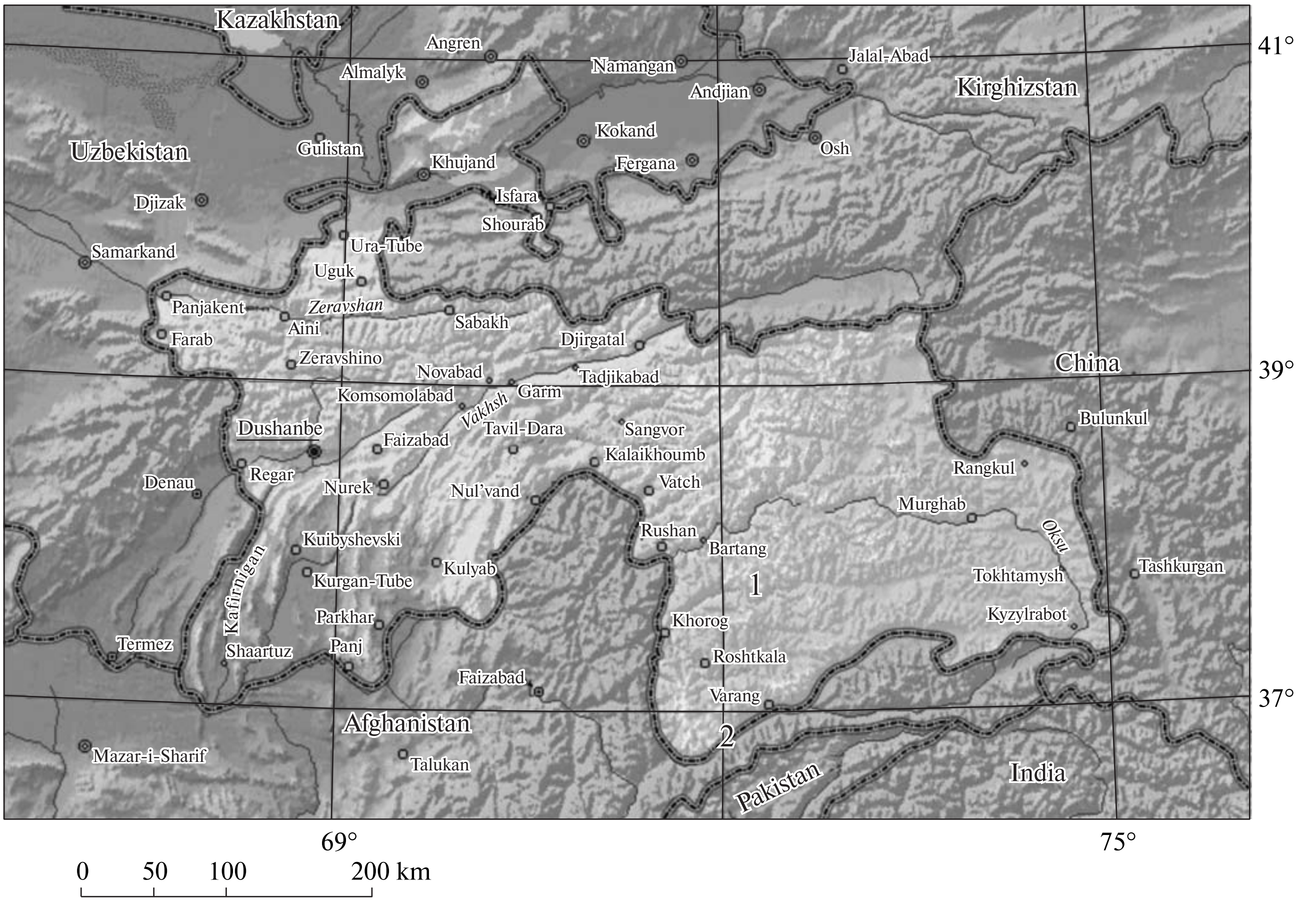

Fig. 1. Location of the objects of study in Tajikistan: (1) the Gunt River valley; (2) the Panj River valley.

Pamir river valleys, where the arable lands are located. According to the meteorological data, in the Western Pamirs the total precipitation in the past decades increased by 25% compared to the middle 20th century but in the Eastern Pamirs decreased by 25–50% [22].

The arid climate determines the low relative air humidity: 43–45%. The changes in the temperature with altitude vary among the Western Pamir regions. The average gradient of the changes in the mean annual temperature is 0.8°C per 100 m of altitude with variations of 0.4 to 1.0°C. The lowest gradients are observed in the Khorog–Ishkashim region for both the mean annual temperature and the sums of temperatures >0, >5, and >10°C. This indicates warmer climatic conditions in the Southern part of the Western Pamirs. However, the orography also plays an important role in the change of the temperature trend in these regions. The climatic zones shift upward when going from the North to the South of the Western Pamirs. The mean maximum soil temperature in the Western Pamirs in July is 58–63°C, and the mean minimum temperature is 11–16°C. The Ishkashim district is characterized by intense wind conditions.

The relief and climatic conditions largely determine the agricultural potential of the Pamirs, especially in the altitude belt of 2600–3500 m asl. The pedogenesis processes are relatively slow because of the arid climate and long winters. The soils of the Pamirs have been studied by many researchers [1, 12–14, 28]. These are shallow and low-humus soils [11, 15]. The latest thorough soil mapping of the Pamirs on a scale of 1 : 10000 was performed by the “Tadgiprozem” Institute in the 1970s [15]. The soil type, texture, and the contents of humus and nutrients were determined. Uneroded and slightly, moderately, and strongly eroded soils were identified using the soil morphological method. Cherbar’ recently developed a classification for the Western Pamir soils [27]. We acquired new data about the state of the soil cover on the bottoms of river valleys in the altitude belt of 2600–3400 m asl and revealed the reasons for and rates of the land degradation.

OBJECTS AND METHODS

A quantitative assessment of the current state of the soils and their degradation rates was conducted on valley bottoms in the middle course of the Gunt River (Shugnanskii district, GBAR) and the upper course of the Panj River (Ishkashim district, GBAR) (Fig. 1).

These regions were selected because of their location in the altitude belt of 2600–3400 m and the difference between their soil covers. In this altitudinal zone, the climatic changes most significantly affect the productivity of the soils, and the degradation of the soils provoked by inadequate agricultural practices further decreases their fertility[36].

The Gunt is a right tributary of the Panj; it flows from east to west and enters the Panj in the region of the city of Khorog. During the Pleistocene, the river valley was occupied by a glacier; after its thawing, a system of lakes was formed upstream of the terminal moraines. After the natural emptying of lakes because of the cutting of the terminal moraines by the river flow and the simultaneous entrenchment of the river into lacustrine sediments, the former lake bottoms became river terraces, which are presently the major agricultural lands. The detrital material arriving from the valley slopes and tributaries forms alluvial cones and benches, which are also partially used as arable lands. The studies of the soil cover on the Gunt River bottom were performed at altitudes of 3000–3400 m asl. In this altitude zone, dark brown alpine semidesert soils prevail in the valley bottoms of the Gunt and its tributaries [12, 27]. The area is characterized by the sum of effective temperatures of 900–2000°C; the annual precipitation is 300–400 mm at the rainfall factor of 0.3–0.5.

The studied area of the Panj valley bottom occurs above 2600 m asl between the settlements of Darshai and Shitharv. Gray-pale desert soils occur in the valley bottom in the altitude belt of 2400–3000 m [12, 27]. In this altitude zone, the sum of the effective temperatures is 2000–3100°C; the annual precipitation is insignificant (100–130 mm) with a rainfall factor of 0.07–0.10. The cultivated lands occupy the first rock-protected alluvial terrace mainly composed of glacial sediments and covered by numerous proluvial cones. The cropland also occurs on some valley sides and fragments of older glacial terraces located significantly higher than the current level of the Panj.

The major part of the arable land in the studied regions is irrigated. The furrow irrigation technique is used. Each allotment owner applies water without any rules. The irrigation pattern of the stony soils was early studied both under field conditions [2, 22, 25, 26, 29] and in the course of laboratory experiments to assess the erosion resistance of soils for developing a predicting model of irrigation-induced erosion [3, 4]. Cereals (wheat, barley) and potato are the main crops grown on the irrigated lands; orchards are also cultivated if the temperature is sufficiently high. Perennial grasses are sown on some areas, mainly in the Gunt valley bottom. Steep valley slopes with shallow very stony soils are used for sparse pastures and hayfields [12, 27].

The work involved the study of the physicochemical properties of the soil cover on virgin and arable lands, including the pH; the texture; the water permeability; and the contents of humus, nutrients (phosphorus and potassium), and carbonates. The texture of the soils was assessed by the Kachinskii method, the content of humus was determined by the Tyurin method, the bulk density was determined by the cutting ring method, and the soil permeability was measured by the ring method. Two rings 60 and 20 cm in diameter were used. The content of P_2O_5 in the soil was determined by the Machigin method, and the content of K_2O was determined using a flame photometer.

The radiocesium method was used for assessing the redistribution rate of the soils of plowland. This method is widely used for assessing soil erosion and sediment accumulation in different regions of the world [8, 30–32, 34, 37, 40, 44]. The method is based on using the ^{137}Cs isotope of anthropogenic origin as a tracer. Its genesis is related to the simultaneous beginning of nuclear explosions in the open air in the USSR and the United States in the early 1950s. At the moment of an explosion, ^{137}Cs, which is a fission product, got into the stratosphere; at the formation of cauliflower clouds, it gradually came to the atmosphere and then arrived onto the earth's surface with precipitation. When it arrived onto the surface of the soil, ^{137}Cs was rapidly and strongly fixed on the soil particles and then migrated only together with them [8, 10]. The main principle of the method is based on the assessment of the changes in the total ^{137}Cs reserve at the surveyed sites against the reserve on the reference plot without erosion–accumulation processes. The major fallout of the ^{137}Cs of global (bomb) origin occurred during the period from 1954 to the early 1980s with the main maximum in 1963 [19]. After the signing of the treaty banning nuclear tests in the atmosphere in 1963, the ^{137}Cs fallouts continuously decreased. Along with the global fallouts, ^{137}Cs fallouts from the atmosphere due to technogenic accidents occurred in different regions of the world. They are characterized by great nonuniformity and significantly smaller coverage. The main limitation of this method is related to the high variation of the initial ^{137}Cs fallout in separate regions [9, 39, 41]. When the variation exceeds 20–25%, the method cannot be recommended for the quantitative assessment of the sediment redistribution rate. For mountain regions with the highly contrasting precipitation layer, a correlation between the initial ^{137}Cs fallout and the altitude of the country was found [31]. Therefore, in mountainous areas, reference plots should be selected for determining the initial isotope fallout in the same altitude range where the test area occurs.

On the reference plots and the arable lands where the sediment redistribution rate was studied, integral samples were taken from the 0- to 25-cm layer in triplicate at each sampling point using a cylindrical sampler with an inner diameter of 20 cm. A sample from the 25- to 35-cm layer was also taken from each area of potential sediment accumulation. On the reference plots, layered soil samples were taken from a fixed area in a profile to a depth of 35 cm with 5-cm intervals to

Table 2. Particle size distribution in soils of the studied river valleys

Profile no.	Depth, cm	Content of fractions						Total <0.01
		1.0–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
Soils of the Gunt valley, Shugnanskii district								
R-1f, virgin soil	0–17	23.4	29.8	33.6	6.8	3.2	3.2	13.2
	17–38	19.2	35.8	31.2	4.0	7.6	2.2	13.8
	38–60	25.8	29.2	23.4	6.6	10.6	4.4	21.6
	60–100	12.8	23.8	33.0	9.4	13.0	8.0	30.4
R-2f, irrigated plowland	0–17	23.1	29.9	29.0	6.2	8.2	3.6	18.0
	17–45	19.9	14.1	49.4	5.4	8.6	2.6	16.6
	45–67	22.7	26.7	23.2	10.4	13.4	3.6	27.4
Soils of the Panj valley, Ishkashim district								
R-1f, irrigated plowland	1–30	8.2	44.4	34.4	5.6	5.6	1.8	13.0
	30–50	17.3	51.4	18.0	4.8	6.4	2.2	11.4
R-2f, irrigated plowland	0–30	6.6	54.96	20.8	6.4	7.2	4.0	17.6
	30–50	25.3	47.7	12.6	2.6	6.2	5.6	14.4
Pr-17, virgin soil	0–30	9.9	52.3	29.8	2.2	3.4	2.4	8.0
	30–50	29.6	51.2	12.8	2.4	2.6	1.4	6.4
Pr-20, virgin soil	0–30	21.4	50.8	20.4	1.6	4.0	1.8	7.4
	30–50	33.1	38.5	19.0	2.6	4.2	2.6	9.4

determine the vertical distribution of the isotope and its penetration depth into the soil.

The preparation and analysis of the samples for ^{137}Cs were performed at the Research Institute of Soil Science of the Academy of Agricultural Science of Tajikistan. The preparation of the samples for the γ-spectroscopic analysis included their drying at 105°C and grinding to the fraction of <0.75 mm. The analysis was performed using an ORTEC γ-spectroscopy system with a high-resolution coaxial germanium semiconductor detector with an efficiency of 40% (model GEM-M5970P4-S). The exposure time was determined by the statistically reliable fixation of the ^{137}Cs peak at 661.66 keV and varied from 10000 to 60000 s. The processing of the obtained spectra and the calculation of the activity were performed using GammaVision-32 software.

A proportional model was used to calculate the erosion and accumulation rates on the arable plot from the content of ^{137}Cs in the soil [43]. The model is based on the supposition that the entire reserve of the radionuclide is uniformly distributed throughout the plow horizon. The rate of the soil erosion or sediment accumulation was calculated from the following equation:

$$R = 10 \times \frac{BZ_P}{\Delta t}\left(\frac{A - A_{ref}}{A_{ref}}\right), \qquad (1)$$

where R is the erosion/accumulation rate (a negative value corresponds to erosion, and a positive value corresponds to accumulation), t/ha per year; Z_P is the depth of the plow horizon, m; B is the soil density, kg/m^3; Δt is the time of the erosion or accumulation assessment, years; A is the radionuclide reserve at the site, Bq/m^2; A_{ref} is the reference value of the ^{137}Cs reserve, Bq/m^2; and 10 is the conversion factor from kg/m^2 to t/ha.

The duration of the assessment period was selected with consideration for the time elapsed from the maximum ^{137}Cs fallout (1963) to the sampling moment (2009–2010).

RESULTS AND DISCUSSION

Soil properties and their changes under plowing. The soils in the Gunt valley bottom usually have a sandy loamy to loamy sandy texture, while a sandy–loamy sandy texture is more typical for the soils in the Panj valley. The irrigated arable soils generally have a heavier texture than the virgin soils. No clear trend is observed for the changes in the contents of different fractions with depth in the soil profile; the distribution of the fractions depends on the composition of the parent rocks (Table 2). Stony soils occupy significant areas on the studied plots. The content of stones in the soils in the Panj valley bottom is significantly higher than in the Gunt valley bottom. The irrigated lands have a lower content of stones and deeper soils than the virgin lands. On the plots in the Panj valley, the irrigated and unirrigated lands mainly include shallow medium and strongly stony soils underlain by boulder–rubbly sediments with a loamy sandy–sandy filler.

The content of humus in the dark brown alpine semidesert soils in the Gunt valley bottom is almost double that in the gray-pale mountain desert soils in the Panj valley bottom. The reserves of humus in the stony soils vary in a wide range and decrease proportionally to the content of stones (Table 3).

The content of carbonates in the soils is determined by the composition of the parent rocks. The soils in the

Table 3. Contents and reserves of humus in soils of the studied plots

Layer depth, cm	Humus content range	Mean humus content	Humus reserve range	Mean humus reserve in the soils			
				nonstony	slightly stony	moderately stony	strongly stony
	%		t/ha				
Gunt River valley							
0–30	1.11–3.88	2.49					
30–50	0.67–3.03	1.85					
0–50	0.89–3.45	2.17	61–232	147	110	74	37
0–100	1.22–2.20	1.71	166–299	233			
Panj River valley							
0–30	0.54–2.01	1.28					
30–50	0.35–1.68	1.00					
0–50	0.44–1.84	1.14	27–114	71	53	36	18
0–100	0.81–1.29	1.10	50–80	65			

Gunt valley occurring on the morainic sediments, whose detrital material consists of acidic rocks (granites, granitoids), contain no $CaCO_3$. Only in separate horizons does its content reach 1.0%. The soils developed on moraines in the Panj valley contain no carbonates, while their content in the soils on the gneiss cones is in the range of 1–5% and sometimes reaches 9%. The soil reaction also varies depending on the content of carbonates. The moderately cold dark brown alpine semidesert soils have a wider pH range (from 5.8 to 7.8). The moderately warm gray-pale mountain desert soils are characterized by high pH values (7.9–9.3), which can be related to the content of magnesium carbonate.

The bulk density of the plow horizon in the irrigated nonstony soils is usually in the range of 1.03–1.46 g/cm^3 on all of the plots with the soil porosity being 61.7–45.7%. In the moderately and strongly skeletal soils, the bulk density of the fine earth in the humus horizon varies from 1.24 to 0.9 g/cm^3, respectively. The lower values of the bulk density in the strongly skeletal soils are due to the presence of voids formed by the skeleton. In the lower horizons, the bulk density increases to 1.38–1.66 and 1.3–1.40 g/cm^3 in the nonstony and stony skeletal soils, respectively. Therefore, the soils have a low water capacity because of their stoniness, light texture, and low depth.

Table 4. Portions (%) of the studied plowland areas with different nutrient supplies

District	Degree of supply	P_2O_5	K_2O
Shugnanskii district, the Gunt valley	Unsupplied	62	12
	Poorly supplied	19	31
	Moderately supplied	9	27
	Well supplied	6	18
	Very well supplied	4	12
Ishkashim district, the Panj valley	Unsupplied	94	26
	Poorly supplied	3	49
	Moderately supplied	3	11
	Well supplied	abs	6
	Very well supplied	abs	8

The fertility of the soils depends not only on their physical and chemical properties but also on their nutrient supply. The contents of available phosphorus and exchangeable potassium are usually low in the soils. The 0- to 50-cm layer of the arable soils in the Gunt valley contains, on the average, 19.5 mg/kg phosphorus and 28 mg/100 g potassium; in the soils of the Panj valley bottom, the corresponding values are 6.4 mg/kg and 19.1 mg/100 g. The portions of the studied plot areas with different phosphorus and potassium supplies are given in Table 4.

The water permeability of the irrigated soils is usually high and very high; it varies in the range from 0.79 to 4.26 mm/min. The rainfed lands are characterized by a wider range of water permeability (from 0.09 to 5.8 mm/min), which is related to the lithological structure and the high content of stones in the soils. (The field determination of the soil water permeability was performed by G. A. Nekushoeva).

The assessment of the degradation rate of the arable soils in the studied area was performed with the use of ^{137}Cs as a tracer. To determine the initial isotope fallout, a reference plot was selected on each of the studied areas under the supposition that no erosion or accumulation processes occurred on this plot during the period from the beginning of the ^{137}Cs fallout (1954) to the sampling moment.

The reference plot in the Gunt valley occurred on a glacial terrace located to the 3000 m asl and at a height of 25 m above the river level. This was a pasture with minimum slopes. The slope and length of this plot are insignificant, which excludes the possibility of soil erosion. The outwash from any neighboring slope also cannot be redeposited on this plot, because it occurs within the local near-watershed area. The altitude of the plot above sea level is analogous to that of the studied plowland area in the Gunt valley bottom; therefore, the plot can also be used as a reference plot for the determination of the initial isotope fallout on the studied area (with consideration for the above-described changes in the mean annual precipitation and the related ^{137}Cs input from the atmosphere with height).

The layered samples of soils were taken from a fixed area (10 × 10 cm) in a profile to a depth of 35 cm with 5-cm intervals. The content of coarse inclusions of different sizes abruptly increased in the lower horizons. In addition, integral samples of fixed volume were taken from the 0- to 25-cm layer at 11 points using a cylindrical metal sampler. Three samples were taken at each point and mixed for preparing an averaged sample used to measure the content of ^{137}Cs in the laboratory. At a point, three samples were also taken from a depth of 25–35 cm to reveal the portion of ^{137}Cs that could migrate to this depth. Eight sampling points were arranged at equal distances of 3 m from one another. Two sampling points were located in the center of four points earlier arranged as a square, and one point was located apart at equal distances of 2 m from the two other sampling points.

The reference plot in the Panj valley bottom was located in the village of Darshai on the irrigated flat plowland surrounded by trees from three sides. Insignificant erosion can be expected on this field due to the regular irrigation, but its rate should be minimum, because the plot's slope is lower than 1%. The profile for layered sampling was located in the center of the field. Seven samples were taken by layers with 5-cm intervals, except for the first sample taken at a depth of 0–10 cm, from an area 15 × 15 cm in size. Integral samples of fixed volume were taken from the 0- to 25-cm horizon at 12 points arranged in a spiral using a cylindrical metal sampler. For each point, an average sample was prepared by mixing the samples from three separate sampling operations, as was described above for the reference plot in the Gunt valley.

The vertical distribution of ^{137}Cs in the profiles of the studied reference plots is shown in Fig. 2. On the reference plot in the Gunt valley, the isotope concentration is the maximum at the surface of the soil and decreases with depth (Fig. 2a). This suggests that the plot has not been plowed since the beginning of the ^{137}Cs fallout. The absence of the ^{137}Cs of global origin deeper than 15 cm is also typical for many other regions of the northern hemisphere [35, 42]. On the reference plot in the Panj valley bottom, the ^{137}Cs is uniformly distributed within the plow layer to a depth of 25 cm. An analogous distribution of ^{137}Cs was found for the reference plots located on plowlands in other regions [32, 33].

The spatial variability of the initial ^{137}Cs fallout on the two studied reference plots was 17% (Table 5), which corresponds to the variation levels revealed for other regions of the northern hemisphere [9, 35, 38, 41]. It should be noted that the difference in the average content of ^{137}Cs on the two plots coincides with the difference in the annual precipitation between these plots. The initial variation of the ^{137}Cs fallout does not exceed 20%; therefore, the radiocesium method can be used for assessing the redistribution rate of the soils on the irrigated lands in the studied altitude zones of the Gunt and Panj valley bottoms.

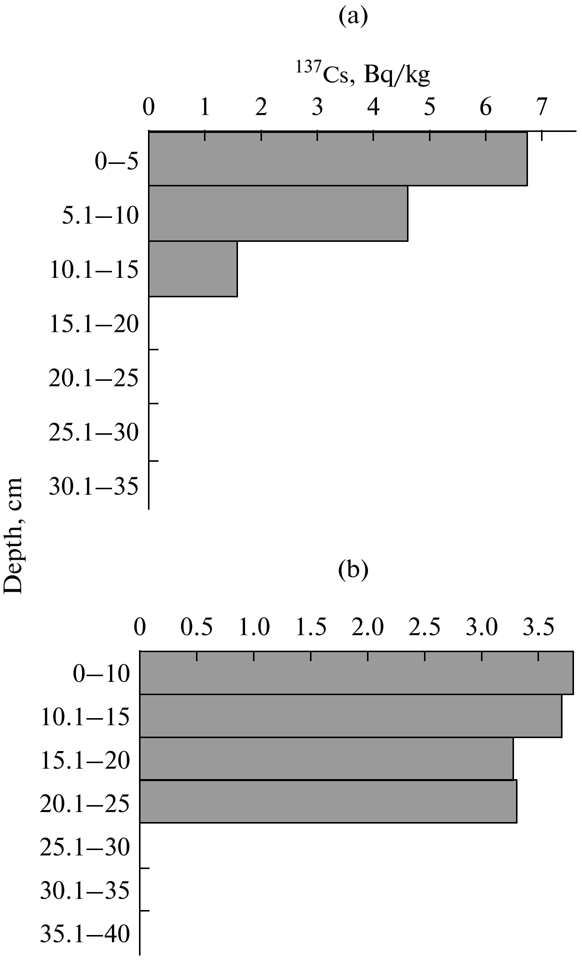

Fig. 2. Vertical distribution of ^{137}Cs on the reference plots: (a) the Gunt River valley (undisturbed soil); (b) the Panj River valley (plowland).

For assessing the sediment redistribution rate, three plots were selected on the arable soils in the Panj valley bottom, including two plots to the north from the set-

Table 5. Statistical characteristics of the ^{137}Cs content variation on the reference plots

Statistical parameters	The Panj valley	The Gunt valley
Mean, Bq/m^2	537	798
Median, Bq/m^2	528	771
Standard deviation, Bq/m^2	93	136
CV, %	17	17
Standard error of the mean, Bq/m^2	±44	±62

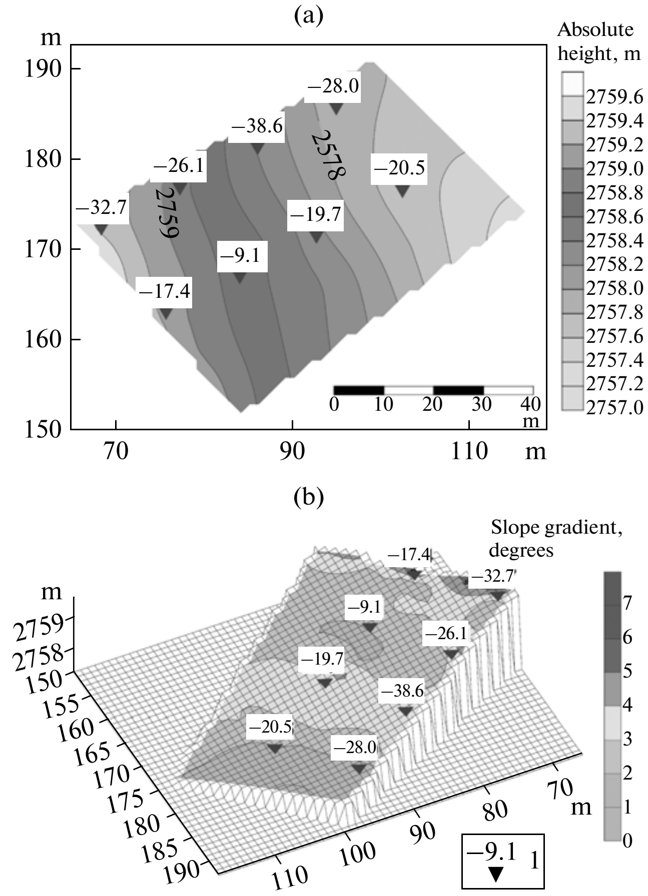

Fig. 3. Irrigated plowland at the settlement of Shitharv: (a) sediment redistribution rates as determined by the radiocesium method and (b) slope gradient map for the same plot.

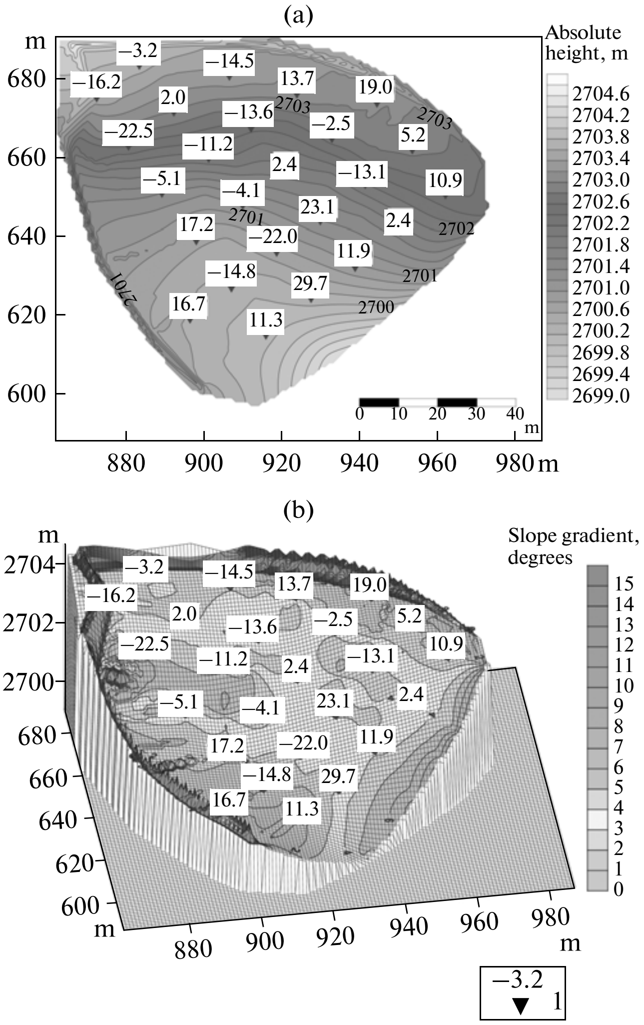

Fig. 4. Five transects on the irrigated plowland at the settlement of Darshai: (a) sediment redistribution rates as determined by the radiocesium method and (b) slope gradient map for the same plot.

tlement of Darshai and one plot to the north of the settlement of Shitharv. The plots differ in the configuration of the slopes. The sampling transects were oriented along the irrigation furrows on all of the plots. A proportional model was used to calculate the erosion and accumulation rates from the content of ^{137}Cs [43].

A clear dependence of the soil erosion rate on the slope angle of the furrow irrigated plot was revealed. The mean soil loss on the plot near Darshai was 24 t/year with the maximum rate (>30 t/ha) being observed on the slopes >3°. An analogous tendency was revealed for the relatively short slope on a plot at Shitharv, where the maximum soil loss was revealed in the middle part of the slope, where its gradient exceeds 3° (Fig. 3). The irrigation furrows were no longer than 45 m on each of these plots.

A radically different situation was revealed on the other plot near Darshai. Here, the direction of the irrigation furrows does not coincide with the maximum slope gradient in most cases (Fig. 4). Therefore, an alternation of the erosion and redeposition zones in accordance with the changes of the gradients is observed along the furrows. In most cases, the gradient along the irrigation furrow is lower than the local gradient of the slope, which favors the redeposition of a significant part of the sediments within the plowland if the total length of the furrows is about 100 m, and the total loss of sediments from this field is almost zero. Only in the upper Northwestern corner of the field strong erosion is observed, because the direction of the irrigation furrow coincides with the slope and its gradient is >3° (Fig. 4). Additionally, a part of the accumulated material is distributed again on the plot thanks to the mechanical movement of the sediments deposited in the irrigation channels, during their regular clearing. This supposition is confirmed by the accumulation observed at all the sampling sites located in the furrow traversing the Northeastern field edge alongside the drainage water channel.

The sediment redistribution rate on the plowland on the Gunt valley bottom was assessed on the plot near the settlement of Mienshakhr. This is a typical plot composed of several small arable allotments separated by irrigation channels (aryks) and characterized by a slight increase of the slope towards the Gunt River. The direction of the irrigation furrows coincides with the slope gradient on all the allotments (with one exception), which favors the development of erosion. However, the plowland slopes are flatter than 3° (Fig. 5). Therefore, the local redistribution of sediments is typical for the plots at soil loss rates in the range of 1–24 t/ha per year and accumulation rates in the range of 1–27 t/ha per year. The eroded plots are obviously located in the upper parts of the furrows, and the accumulation zones occur in the middle and lower parts of the furrows. As a result, the total removal of sediments beyond the studied plot is only 2 t/ha per year (Fig. 5).

The plowlands in the Gunt valley bottom occurring above 3000 m asl usually have slopes <3°. This suggests that the degradation of soils due to water erosion is insignificant there. The large plowland areas under perennial grasses, which protect the soil from erosion even under inadequate irrigation, also confirm this supposition.

Nonetheless, slopes >3° are typical for some plowland areas occupying the relatively steeper alluvial cones of the tributaries. The irrigation-induced erosion rates on these fields can be comparable to those determined on the plots with analogous gradients in the Panj valley bottom. This supposition is confirmed by the remaining network of erosion rills in the lower parts of slopes at the plowland boundaries and the
3 signigicantly lightened soil surface color indicative of a very low humus content. The obtained results about the significantly lower degradation of the soil cover because of the development of erosion processes in the Gunt valley bottom compared to the soils in the Panj valley bottom explain the differences in the contents of humus and nutrients in the soils of the studied regions (Tables 4, 5).

According to the obtained estimates, the largest soil losses (more than 30 t/ha per year) are observed on the irrigated lands with slopes >3° when their gradients coincide with the general slope direction and their length does not exceed 50 m. On the supposition of the constant frequency and intensity of irrigation, this means that no less than 12 cm of soil (i.e., about half of the plow layer) was removed during 50 years of regular irrigation. At the slopes <3°, the soil losses vary in the range of 0–20 t/ha per year. When the furrow length exceeds 50 m, partial accumulation of sediments in furrows is observed, which slightly reduces the portion of sediments removed beyond of the plowland. It can be stated that irrigation-induced erosion is the main reason for the degradation of the topsoil on the irrigated lands in the bottoms of Western Pamir valleys located above 2600 m. The effect of wind erosion observed in the Panj valley affects the degradation of the plowlands on the valley sides. The plowland in the valley bottoms is relatively little subjected to wind erosion due to the protective tree and shrub belts and the more stable structure of the soil aggregates. If the wind erosion had been more intensive, it would have masked the revealed relationships between the erosion rates and the slopes of the irrigation furrows, because wind erosion usually results in significant losses of soil on the upwind slopes and the accumulation of material on the downwind slopes regardless of the ratios of their gradients.

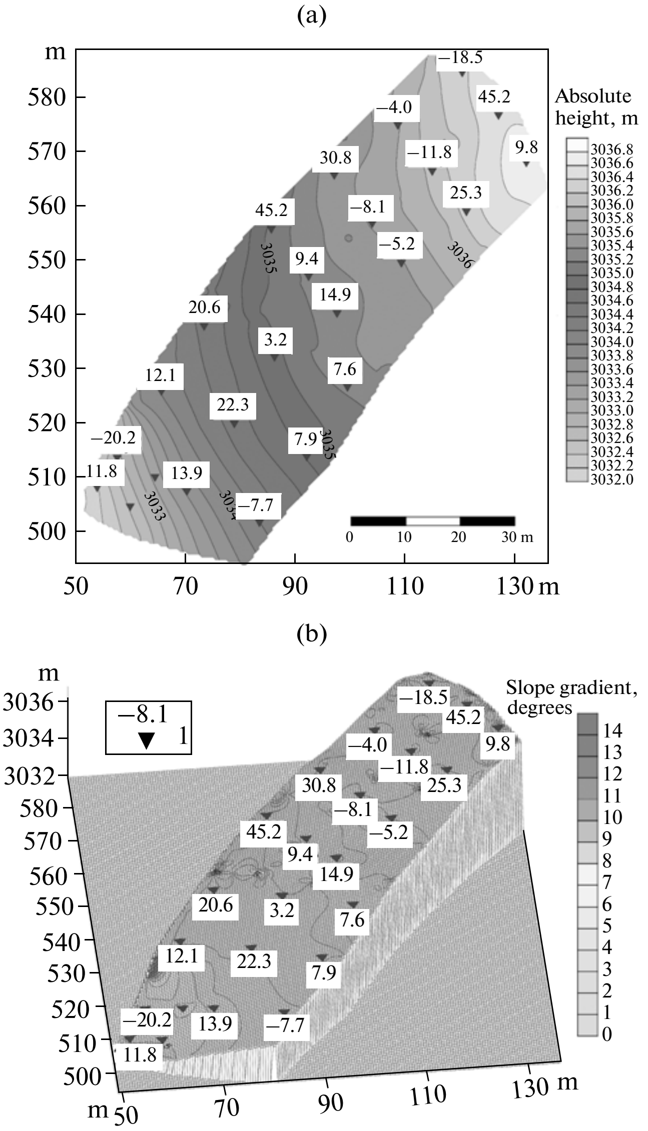

Fig. 5. Three transects on the irrigated plot at the settlement of Mienshakhr in the Gunt River valley: (a) Sediment redistribution rates determined by the radiocesium method and (b) slope gradient map for the same plot.

In general, the rate of the irrigation-induced erosion on the irrigated lands occurring in the Panj valley bottom between the settlements of Shitharv and Darshai is significantly higher than that in the Gunt valley bottom at the settlement of Mienshakhr. This is related to the steep slopes of the irrigation furrows predominantly located on the alluvial cones. The higher degree of degradation of arable lands in the Panj valley bottom is confirmed by the lower contents of humus and nutrients compared to the arable soils of the Gunt valley bottom. The soils in the Gunt and Panj valley bottoms above 2600 m asl are characterized by their low fertility, which is primarily due to the unfavorable climatic conditions for pedogenesis. The excess irrigation of arable lands, especially at the establishment of irrigation furrows along the slopes with gradients >3°, favors the development of intense soil erosion and results in the removal of nutrients beyond the soil profile, which further reduces their contents. In addition, the high infiltration of the current furrow irrigation technique and incorrect irrigation rates results in the irrational water loss due to infiltration.

CONCLUSIONS

The arable soils in the Gunt and Panj valley bottoms in the alpine belt of Western Pamirs contain, on the average, 6.4–19.5 mg/kg phosphorus and 19.1–26 mg/100 g potassium and an average humus content of <2.5%, which suggests their low fertility. This is related to the unfavorable climatic conditions for pedogenesis, on the one hand, and the poorly controlled excessive irrigation favoring the removal of soil particles and nutrients, especially in irrigation furrows with slopes >3°, on the other hand. The radiocesium method showed that the mean annual soil loss can exceed 30 t/ha per year on slopes >3°. In general, the arable soils of the studied plots in the Panj valley bottom were more strongly degraded than the soils in the Gunt valley bottom, which is due to the higher gradients of the arable slopes of the Panj valley bottom, because the plowlands mainly occupy the alluvial cones in the Panj valley and the terraces in the Gunt valley. The climatic conditions of pedogenesis in the Gunt valley at altitudes above 3000 m are less favorable than those of the Panj valley in the altitude belt of 2600–3000 m because of the shorter frostless period. The observed tendency of some increase of the atmospheric precipitation in this Pamir region during the past decades has almost no effect on the pedogenesis processes, because the excess precipitation mainly occurs during the cold period and evaporates at the gradual increase of the mean daily air temperature.

The reveled soil losses can be significantly reduced by cutting of irrigation furrows with gradients <1° and the simultaneous significant decrease of the irrigation rates, as well as the stricter control of these rates. The determined high water permeability of the arable soils suggests the use of short-term irrigation for wetting the plow layer. The current method of irrigation is not standardized, which results in the unjustifiable water consumption and the loss of nutrients because of their vertical migration beyond the root-zone of field crops and lateral removal due to surface runoff. An increase in the productivity of irrigated lands can be reached by increasing the area cultivated with perennial grasses. Their portion can be increased to 50% in the Panj valley bottom and to 50–75% in the Gunt valley bottom. The productivity of perennial grasses is significantly higher than that of the currently grown cereal crops, which are also predominantly used for forage.

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SPELL: 1. analzyed, 2. indentified, 3. signigicantly