Soil erosion, nutrient migration and surface water pollution in Russia

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Abstract The evaluation of soil erosion-originated transport of nutrients (C, N, P, K) from arable slopes is presented in this paper. The results are based on the map "Erosion-affected land in Russia" (scale 1:1 500 000) and agrochemical data. Annual N, P and K losses (in gross forms) are estimated to be 1.4, 1.1 and 11.8 × 10^6 t, respectively. Soluble forms of P (phosphorus) and K (potassium) are exported at the rate of 53 and 68 × 10^3 t, respectively. Average annual soil loss from arable land of Russia is about 560 × 10^6 t, including 26.3 × 10^6 t of humus. Landscape zones and, most importantly, arable land topography, are major factors controlling regional variability of nutrient losses. Conditional P concentration is directly proportional to the amount of its erosion-originated loss and is inversely related to runoff layer. The P conditional concentration (C_{cP}) calculations for all drainage basins of large Russian rivers have been used for to assess the ecological risk of surface water pollution. The North-Caucasian rivers appear to be the most endangered from this point of view.

Key words conditional concentration; delivery from slopes; erosional losses; gross content and soluble forms; human-accelerated erosion; landscape zones; nutrients; pollution; Russia; surface water

INTRODUCTION

Soil erosion is the main agent of lateral material transport on anthropogenically disturbed land. Its intensity in temperate climate zones is 2–3 times higher on arable slopes than under natural vegetation. The total mass of soil being annually washed off agricultural land in Russia is estimated at about 560 × 10^6 t (Litvin, 2002).

Human-accelerated soil erosion has important implications for landscape ecological conditions. Firstly, nutrient (N, P, K) export from slopes decreases soil fertility. Secondly, surface waters are polluted by mineral and organic substances held by transported sediment (sometimes toxic or radioactive). Human-accelerated soil erosion is the main source of river suspended sediment in plain areas. This conclusion is confirmed by an increase of specific suspended sediment yield by 5–8 times in intensively used drainage basins (Hudson, 1971; Dedkov & Mozzherin, 1984; Razgulin, 1993). This paper aims to assess the amount and intensity of nutrient losses from arable slopes in various natural zones and to evaluate the potential risk of surface water pollution in Russia.

METHOD

This study has been based on a cartographic method—the overlay of erosion intensity maps on maps of soil types. Annual soil erosion rates on arable land have been obtained from the map "Erosion-affected land in Russia" (scale 1:1 500 000) (Litvin, 2002). Average annual rates (t ha^{-1} $year^{-1}$) shown on that map were calculated using the modified models USLE (USA) and GGI (State Hydrological Institute, St. Petersburg, Russia) which were adapted for North Eurasian conditions (Larionov, 1993). The point-statistical method of slope morphometry measurement (70–80 × 10^3 points) has allowed us to evaluate variability of soil loss rates on large parcels of arable and pasture land. Adequacy of the modelling has been confirmed by field measurements in key areas. For chernozem soils of European Russia, the error term does not exceed 3–60%. For soddy-podzolic soils, erosion rates may have been overestimated by 20–30% (Litvin, 2002).

Soil nutrient content is closely related to humus content and texture. For most chemical elements there are typical stable ratios between soluble and insoluble forms (for example, 1:10–1:15 for phosphorus). This makes it possible to use soil type maps for territorial evaluation of soil nutrient content.

Amounts and ratios between different forms of nutrients exported from slopes depend on a number of factors such as soil loss intensity, contribution of rainfall and snowmelt erosion, degree of particle size selectivity, type of crop rotations, etc. Nevertheless, analysis of measurements of soil erosion and nutrient output from erosion plots (Azhigirov *et al.*, 1987; Zhilko *et al.*, 1999) showed that it is reliable to employ estimates of average annual erosion rates for large-scale evaluation of nutrient transport (Litvin & Kiryukhina, 2004). Nutrient fluxes from slopes were estimated combining information on average soil erosion rates, soil type and topsoil nutrient content for various soil types, derived from sources explained for each study point.

Risk of river water pollution is determined by the amount of a pollutant, its toxicity and concentration. To assess the potential concentration of erosion-derived pollutants in river waters, a value of conditional concentration C_c (mg l^{-1}) has been employed:

$$C_c = 10 \cdot A \cdot S \cdot P/H \quad (1)$$

where A is soil erosion rate (t ha^{-1} $year^{-1}$); S is percentage of arable land relatively to total drainage area (%); P is relative pollutant content (gross forms) in the plough layer (%); H is average annual runoff depth (mm). Conditional concentration characterizes gross amount of a pollutant in a unit volume of eroded soil. To derive real concentrations of pollutant in surface waters from that value it should be multiplied by the ratio of soluble and insoluble forms.

It is known that the proportion of slope-derived sediment reaching permanent water objects is inversely related to the drainage basin area. Most of the sediment is deposited in small valleys of ephemeral streams, small lakes, ponds and reservoirs, as well as on slope sections covered with natural vegetation. The general form of the relationship between drainage area and sediment yield reduction is similar for the USA and European Russia territories:

$$K_n = aF^{-0.2} \quad (2)$$

where K_n is the sediment delivery ratio; F is the drainage basin area (United States Soil Conservation Service, 1971; Sidorchuk, 1995). The coefficient a reflects the influence of a number of factors and varies regionally. For example, for the Dnieper and the Volga River basins it equals 0.25, and for the Dnestr and the Don River basins it equals 0.75 (Sidorchuk, 1995). Sediment redeposition on slopes and within small catchments can potentially be evaluated using models such as CREAMS or WEPP (Kinsel, 1980; Laflen *et al.*, 1991). However, there is no database available for large-scale evaluation in regions of Northern Eurasia. For medium-sized plain rivers of European Russia K_n approximately equals 0.06–0.1.

Soil phosphorus (P) can serve as an indicator of the migration and transfers of soil particle-associated pollutants, such as heavy metals and radionuclides. Phosphorus itself plays a leading role in the eutrophication of water bodies. Agricultural land is a major source of this P, estimated to contribute up to 60–90% of its total surface water content (Khrisanov & Osipov, 1993; Kudeyarova, 1993).

RESULTS AND DISCUSSION

Natural and anthropogenic factors of soil erosion vary significantly between different landscape zones of Russia. Most important for our study are percentage of arable land and typical nutrient content and composition in zonal soils. These differences determine zonal variability of C, N, P and K migration from arable land (Table 1). Differences in rates of N, P and K export in various landscapes are not significant. For humus it is more noticeable, though still lower than zonal and regional variation of its soil content (for example, 2–3 times between Chernozem and Soddy-podzolic soils). The lower intensity of P and K losses in Siberia is a consequence of the limited extent of soil erosion on the West-Siberian Lowland. In general, for landscape zones nutrient export intensity is predetermined by spatial distribution of erosion. The latter is dependent on azonal factors—topography and regional land use patterns.

Losses of humus, N, P and, to some extent K in absolute terms, are substantially higher in landscape zones dominated by Chernozem soils than in those with Soddy-podzolic soils. The European steppe and forest-steppe zones lose 3.2 times more nutrients, and Siberian 4.6 times more, than the taiga forest zones of the same territories (Table 1). The main reasons for this are both higher nutrient content in Chernozems and the larger percentage of arable land. On average 199 kg of humus, 11 kg of N, 8.3 kg of P and 89 kg of K (gross) are lost annually from 1 ha of arable land in Russia.

Table 1 Annual erosional losses of soil, humus and nutrients from arable land of different landscape zones of Russia.

Regions and landscape zones	Eroded soil volume ($\times 10^3$ t)	Losses of humus and gross forms of nutrients							
		Rate (kg ha^{-1})				Volume ($\times 10^3$ t)			
		Humus	N	P	K	Humus	N	P	K
European Russia	436 137	198	11.7	8.7	96.2	18 674	1100	823	9056
Forest, including:	140 089	162	11.7	10.2	129.5	3379	246	213	2707
(1) North and middle Taiga	15 141	156	10.3	9.2	139.1	303	20	18	270
(2) Southern Taiga	124 948	162	11.9	10.3	128.5	3076	226	195	2437
Forest-steppe	148 772	215	12.3	8.3	94.0	6948	394	268	3039
Steppe	147 276	204	11.2	8.4	81.0	8347	460	342	3310
Siberia	130 833	202	9.3	7.1	72.3	7692	356	271	2757
Forest	28 407	208	12.7	8.5	103.0	1223	75	48	572
Forest-steppe	53 092	216	9.4	6.9	66.6	3812	165	122	1175
Steppe	49 334	178	7.8	6.6	67.7	2657	116	98	1010
Entire Russia	566 970	199	10.9	8.3	89.3	26 366	1456	1094	11 800

Table 2 Annual erosional losses of soil, humus and nutrients from arable land of different economic regions of Russia.

Economic regions	Soil loss rate (t ha^{-1})	Eroded soil volume (× 10^3 t)	Humus and nutrient content in suspended sediment (upper figure × 10^3 t; lower figure kg ha^{-1})					
			Gross				Soluble	
			Humus	N	P	K	P	K
Northern	6.3	8207.0	164.14	10.7	9.8	147.7	0.9	1.1
			125.9	8.2	7.5	113.6	0.68	0.76
North-Western	4.6	8447.1	169.0	11.8	11.0	152.0	1.1	1.2
			91.4	6.3	6.0	82.0	0.60	0.65
Volga-Vyatka	8.4	63 472.2	1777.2	120.6	95.2	1206.0	6.5	7.7
			235.2	16.0	12.6	159.6	0.86	1.0
Central	5.0	73 486.9	1984.1	132.3	110.2	1396.3	7.6	7.7
			134.8	9.0	7.5	95.0	0.51	0.52
Central-Chernozem	3.1	33 874.6	2405.0	115.2	67.7	745.2	3.0	3.7
			220.2	10.5	6.2	68.2	0.28	0.34
Povolzhskiy	2.5	62 588.3	3004.3	181.5	112.7	1314.4	5.6	7.5
			120.7	7.3	4.5	53.0	0.23	0.30
North-Caucasian	6.5	105 938.9	6144.5	339.0	264.8	2436.6	7.8	12.0
			376.9	20.8	16.8	149.5	0.48	0.73
Ural	4.0	89 012.8	4895.7	267.0	186.9	1958.3	6.2	10.4
			220.0	12.0	8.4	88.0	0.27	0.47
Western-Siberian	1.3	26 355.0	1408.6	65.0	60.6	553.5	3.1	3.6
			69.5	3.2	3.0	27.3	0.16	0.18
Eastern-Siberian	8.1	77 926.1	3762.1	163.6	148.0	1558.5	8.9	10.7
			391.0	17.0	15.4	162.0	0.93	1.12
Far East[1]	6.0	16 931.3	638.4	47.4	25.4	338.6	2.0	2.3
			226.2	16.8	9.0	120.0	0.70	0.81
Entire Russia[2]	4.3	566 240.2	26353	1454	1092	11807	53	68
			199.1	11.0	8.3	89.7	0.39	0.51

[1]In the Far East region, arable land of Amur, Khabarovsk and Primorskiy regions is also included;
[2]Without Kaliningrad region.

In order to develop and validate national-scale ecological and soil conservation programmes it is necessary to have information on nutrient export from slopes within administrative or economic territorial units (Table 2). Estimations have shown that the migration rates of P and K in soluble forms from arable land are relatively low, both in individual regions and for the whole of Russia. However, gross annual losses for the whole of Russia (52.7 × 10^3 t P and 67.9 × 10^3 t K) are economically serious, especially taking into account the high prices of artificial chemical fertilizers.

Average annual rates of nutrient migration vary regionally: for N and P from 7 to 12 kg ha^{-1}, for K from 6.5 to 14.7 kg ha^{-1}. Lower rates are observed in the Central-Chernozem and Volga regions where arable Chernozems prevail. Minimum values are found for Siberia as soil erosion there is only active locally in the far southeast (Table 2). Maximum migration rates are characteristic for the North-Caucasian region where high erosion rates are combined with relatively high nutrient content in the topsoil. Average annual rates of humus loss from arable land in Russia vary from 70 to 390 kg ha^{-1}. Total export of organic matter from slopes under agricultural land use exceeds 26 × 10^6 t (Table 2).

Results of our calculations of spatial distribution and rates of nutrient migration for European Russia are in satisfactory agreement with the results of other studies based on independent methods (Podgorny & Butenko, 1991; Kashtanov & Yavtushenko, 1997).

Table 3 Characteristics of P delivery into surface water in different landscape zones.

Landscape zones and topography	Number of drainage basins	Gross soil loss on arable land (t ha^{-1} year^{-1})	Specific sediment yield from arable land (t ha^{-1} year^{-1})	Annual runoff layer (mm)	C_{cP} (mg l^{-1})
Forest	**86**	**6.7**	**2.4**	**225**	**1.4**
Lowland	73	6.4	2.1	228	1.1
Upland	13	8.8	4.8	202	3.2
Forest-steppe	**37**	**4.6**	**3.2**	**150**	**4.1**
Lowland	21	3.4	1.8	166	2.3
Upland	16	6.2	5.0	126	6.6
Steppe	**33**	**3.6**	**3.0**	**57**	**10.2**
Lowland	24	2.2	1.8	50	8.2
Upland	9	6.5	5.6	72	13.0

RISK OF SURFACE WATER POLLUTION

Assuming that phosphorus can be used as an indicator of environmental behaviour of many other pollutants exhibiting similar geochemical properties, we have employed the estimated conditional concentration of P (C_{cP}) as an indicator of surface water pollution from erosional sources. The spatial pattern of such pollution is mainly determined by variations in river runoff, soil erosion rate and pollutant concentration in soils (Table 3). Within European Russia these factors, as well as land use characteristics, change according to latitudinal zones. The value of C_{cP} exhibits a similar tendency of variation, with significant additional influence of azonal geomorphic factors. Surface water in drainage basins of the forest-steppe and steppe zones are characterized by the highest C_{cP} values. Water bodies and watercourses of these zones are at largest risk of eutrophication and disappearance. Upland areas are at increased risk of surface water pollution in all landscape zones as more ranged terrain favours erosional transport of nutrients from slopes to river network.

Zonal characteristics can be used to evaluate the potential pollution of small and medium rivers by P. For large rivers an individual approach is preferred (Table 4) as such rivers cross contrasting landscapes with different natural and land use conditions. This causes significant variation of pollution within drainage basins. Major factors controlling the P delivery are the same as for smaller rivers, though the extent of agricultural land becomes dominant for northern European Russia and southeastern Siberia.

The Volga River basin is characterized by the largest internal variation of P pollution. The average soil erosion rate for that area is 6.4 t ha^{-1} year^{-1}, specific sediment yield is 2.8 t ha^{-1} year^{-1}, and C_{cP} is 2.0 mg l^{-1}. The upper part of the Volga River basin is located within the forest zone. The values of C_{cP} in the largest Volga tributaries in forested area vary from 0.1 to 2.5 mg l^{-1}. The steppe part of the basin is characterized by higher values of C_{cP} (2.6–7.5 mg l^{-1}) due to lower surface runoff, despite relatively low erosion rates (1.5–3.9 t ha^{-1} year^{-1}). In the lower part of the basin within the Caspian Lowland erosion-derived P pollution is almost absent.

The North-Caucasian river basins (Manych, Kalaus, Kuma, Terek) have maximum values of erosion-derived P pollution in Russia (up to 44 mg l^{-1}). It is associated with a combination of high erosion rates and low surface runoff. The Kuban River basin located in the same region has much lower average C_{cP} due to large unpolluted water runoff from its mountainous tributaries. The Western Siberia rivers have low potential P pollution. Only the Kuznetsky Alatau and Salair Ridge piedmonts are characterized by an increase in erosion

Table 4 Potential pollution of river water by erosion-derived P in Russia.

Large rivers / Lakes / Seas	Number of drainage basins	Gross soil loss on arable land (t ha^{-1} year^{-1})	Specific sediment yield from arable land (t ha^{-1} year^{-1})	Annual runoff layer (mm)	C_{cP} (mg l^{-1})
Finskiy Bay	2	3.0	0.3	260	0.1
Ladoga Lake	6	3.3	0.2	287	0.1
Ilmen Lake	7	5.2	1.9	246	0.9
Zap. Dvina River	9	5.0	1..5	233	0.7
Sev. Dvina River	5	7.8	0.9	265	0.5
Dnieper River	9	6.3	4.2	158	3.6
Volga River	85	6.4	2.8	196	2.0
Oka River	17	6.7	3.8	166	3.6
Kama River	10	8.2	3.8	192	2.6
Don River	34	4.0	3.4	85	6.6
Severskiy Donets River	4	7.5	6.3	95	11.8
Azov Sea	2	5.2	4.7	30	25.4
Kuban River	5	8.1	4.7	220	4.0
Terek River	2	13.5	10.3	99	22.0
Kuma River	4	10.9	9.1	68	30.0
Ural River	4	1.9	1.2	72	2.7
Ob River	39	2.6	1.0	126	1.9
Irtysh River	12	0.4	0.1	40	0.5
Enisei River[1]	16	6.6	1.9	117	3.2
Lena River[1]	3	18.2	2.8	126	4.0
Baikal Lake[1]	3	15.8	3.2	43	6.0
Amur River[1]	10	11.5	1.7	66	3.8

[1]Within agricultural zone only.

rate and C_{cP} (up to 5–10 t ha^{-1} year^{-1} and 5.5 mg l^{-1}, respectively). The latter is also relatively high in agriculturally developed parts of Eastern Siberia and the Far East (Table 4).

Real concentrations of soluble P in river water is much lower than the estimated C_{cP}, as the latter includes gross P forms delivered from slopes. When accounting for soluble forms only (normally not exceeding 10% of gross value) and making corrections for the sediment delivery ratio, estimates become closer. In the river water of agriculturally developed drainage basins, mineral P concentrations are in the range of 0.002 to 1.145 mg l^{-1} and gross P values are 0.007 to 3.2 mg l^{-1} (Savenko & Zakharova, 1997).

However, absolute values of pollutant concentration do not allow an evaluation of ecological risks. It is necessary in this case to establish "ecological threshold" values of concentration. As regards P, it has been found that water vegetation does not develop when its concentration is below 0.01 mg l^{-1}. Its growth begins in a range of concentrations from 0.01 to 0.025 mg l^{-1}, and it flourishes under higher concentrations—from 0.09 to 1.8 mg l^{-1} (Kudeyarova, 1993). Thus, we can establish the first "ecological threshold" value for P as 0.01 mg l^{-1} (C_{cP} about 1 mg l^{-1}). The second ("crisis") value will be 0.2 mg l^{-1} (C_{cP} about 20 mg l^{-1}, and it is associated with flourishing of water vegetation. Considering these values, we have distinguished five types of areas within the agricultural zones of Russia, according to their risk of water pollution by soil erosion-derived P (Fig. 1). These are based on C_{cP} estimations discussed above.

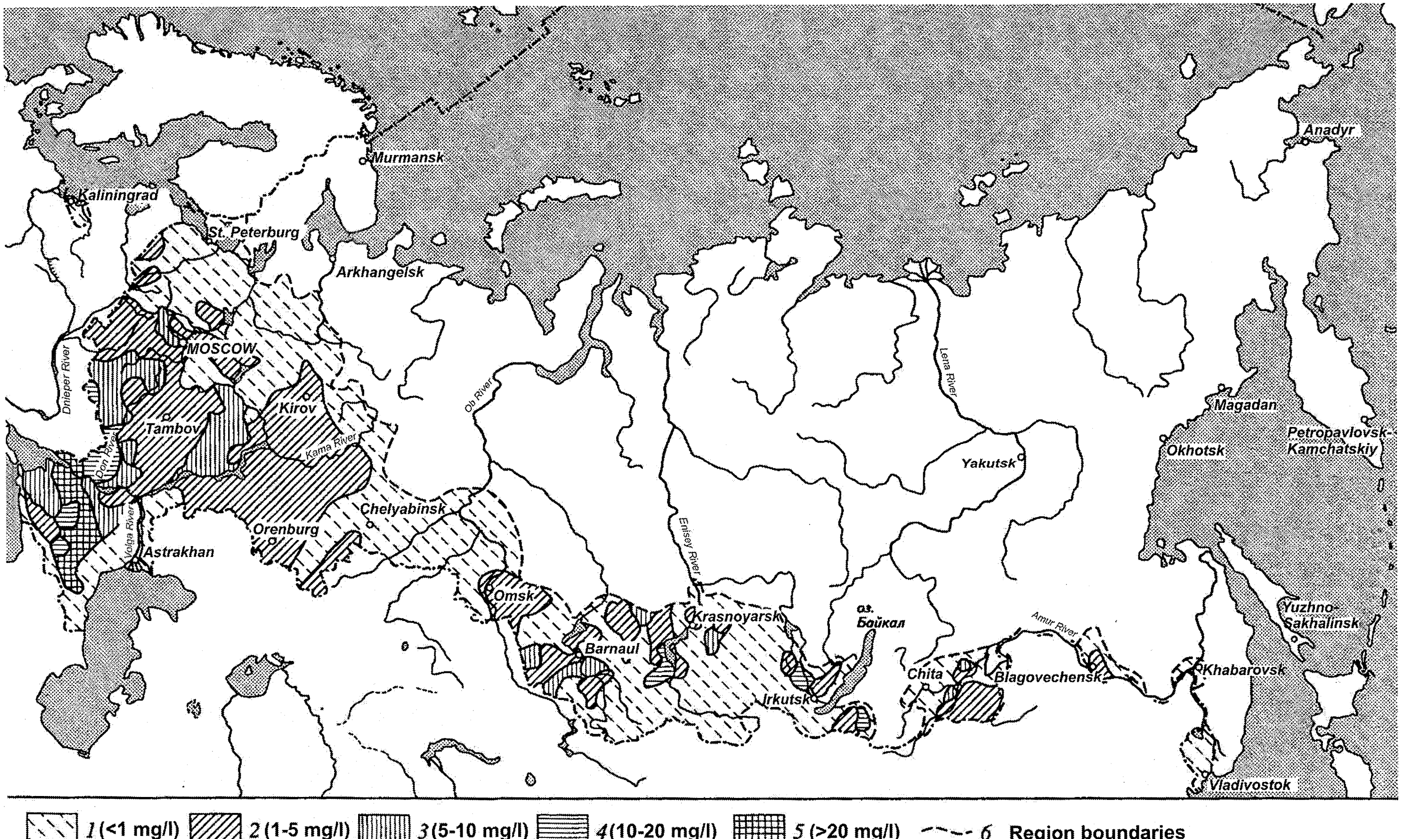

Fig. 1 Potential surface water pollution by erosion-derived P in the agricultural zone of Russia. Five regions are distinguished according to estimated C_{cP} value.

CONCLUSION

Erosion remains the main factor of soil degradation and surface water pollution by nutrients on agricultural land in Russia. Total output of gross forms of N, P and K from arable slopes is 2–3 times higher than its input to fields with organic and mineral fertilizers. Hence, erosion causes substantial economic losses. Annual losses of soluble (readily available for cultural plants) forms of N, P and K comprise about 8% of their mass in mineral fertilizers. Soil erosion is also the main agent of surface water pollution by P.

Regional variation of nutrient erosional transport intensity mainly depends on soil erosion rates. River water pollution is also controlled by variation of specific surface runoff.

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