Soil erosion on the agricultural lands in Southern Siberia: current state, risks, soil protection models

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Abstract. Territorial distribution of agricultural land erosion of in Siberia is considered. We determine different degradation processes mechanisms from west to east. In the Western Siberia meltwater erosion dominates. In the Middle Siberia soil erosion is caused by meltwater and rainstorm runoff, and in the Eastern Siberia by rainstorm discharge. Agricultural lands in mountains located in inter-mountain basins where concentric zoning of changes in mechanisms and rates of land degradation were analyzed. Predictive estimation of soil loss is carried out. We developed maps of erosion-hazard for agricultural lands. Detailed mapping of soil erosion rates in model basins has been carried out. Obtained are the trends and tendencies of soil erosion development in Siberia and the quantitative indicators of potential soil losses from erosion and deflation. Special attention is paid to soil degradation in the Lake Baikal basin. Positive trend of dust storms in the south part of Eastern Siberia at present day indicate aeolian processes increase under climate warming. In future, desertification of steppe landscapes will continue. The probability of desertification of southern Siberia, caused by the development of soil erosion, is determined. Regional models of soil conservation are presented

1. Introduction
Accelerated soil erosion constitutes a very grave consequence of the human irruption into the environment. A complicated ecological situation was also caused by degradation of agricultural lands in the southern of Siberia where the arable land takes more than 25 million ha. Agriculture here has a patchy nature, due to its intermontane location. At the beginning of the 1990s, agricultural lands occupied from 70 to 90 % of this area. Excessive plowing-up of slope areas, combined with large mechanical pressure on soils, gave rise to an intensification of erosion processes. The Khakasia and Buryatia stands out because of its high degree of soil erosion, one of the main criteria for assessing the ecological situation in any region, where this indicator exceeds 80 %, which makes it possible to classify these areas as having an emergency ecological situation (table 1). Active agricultural land use during the 17-20th centuries produced soil degradation. Agricultural lands occupy more than 55 million hectares, and about half of them are plowed. 9.5 million hectares are subject to flushing and deflation in varying degrees (table 1). The attention of researchers to the problems of destruction and degradation of soils in Siberia was attracted in connection with the development of virgin and fallow lands in 1953-1958, accompanied by a sharp activation of erosion processes. In the south of Siberia, comprehensive research was undertaken to protect the soil from erosion and deflation. Presented are regional features of soil erosion, determined are the extent and soil degradation degree in Asian Russia on the basis of generalization of long-term studies of soil erosion.
2. Data and Methods
To ensure environmental safety in the south of Siberia, a network of complex geographic research stations has been established more than 50 years ago, where soil erosion has been studied as one of the most dangerous processes of degradation within the agricultural lands. For the regions of the south of Siberia we obtained long-term experimental data on the rate of natural erosion. They were created in Institute of Soil Science and Agrochemistry SBRAS, Novosibirsk (Khairyuzovskii forest-steppe field station (1971), Ust’-Kamenskii forest-steppe field station (1974), Baikalskii mountain-taiga field station (1972), V.N. Sukachev Forest Institute SB RAS, Krasnoyarsk (Khakasskii field station (1959), V.B. Sochava Institute of Geography SB RAS, Irkutsk (Berezovskii forest-steppe field station (1981), Novonikolaevskii steppe field station (1970), Kharanorskii steppe field station (1961). The Institute of Soil Science and Agrochemistry SB RAS conducted more than 30 years of observations of snowmelt and of soil loss in arable land in various regions of Western Siberia [1]. Particularly detailed studies were carried out in Presalairye, the Kuznetsk depression and Prioby.

In order to prevent further degradation of land resources in the south of Eastern Siberia, it is necessary to develop land-use policies based on land zoning according to the degree of erosion hazard. We carried out such zoning for all the main agricultural areas of the south of Eastern Siberia (the Nazarovskaya, Kanskskaya and Yuzhno-Minusinskaya depressions, the Irkutsk-Cheremkhovo plain, and the Selenga River basin). Quantitative assessment of soil erosion and mapping of erosion-hazardous lands in the south of East Siberia was carried out using the Universal Soil Erosion Equation, modified by the Laboratory of Soil Erosion and Channel Processes of Moscow State University for the territory of Russia. Applying this empirical dependence to determine the average annual soil loss rate in the southern regions of Siberia is confirmed by the data of full-scale measurements of the slope washout rate. The correlation coefficient of the measured and calculated rates is rather high (0.86 ± 0.11). The long-term dynamics of erosion processes is analyzed based on data on the runoff of suspended sediments in 18 basins. Erosion zoning of Siberia was carried out.

3. Results and Discussion

3.1. Processes of slope wash
Here are the data of long-term records of the erosion rate on steppe slopes in undisturbed natural conditions in the south of Siberia. Despite the fact that the measurements were carried out in different

| Region         | Arable lands | Soils | Total degraded soils |
|----------------|--------------|-------|----------------------|
|                |              | Eroded | Deflated | Eroded and deflated | thou ha | % from arable lands |
| Altaiskii      | 7274.7       | 1099.9 | 2364.5   | no                  | 3464.4  | 47                  |
| Mountain Altai | 145.9        | 86.2   | 2.4      | no                  | 88.6    | 61                  |
| Kemerovskaya   | 1613.0       | 144.8  | 173.6    | 74.6                | 393.0   | 25                  |
| Novosibirskaya| 3865.4       | 247.0  | 251.6    | 22.0                | 520.6   | 13                  |
| Omskaya        | 4453.5       | 212.9  | 1294.6   | 254.0               | 1761.5  | 40                  |
| Tomskaya       | 667.0        | 6.3    | no       | no                  | 6.3     | 1                   |
| Tyumenskaya    | 1740.0       | no     | no       | no                  | no      | no                  |
| Irkutskaya     | 1612.4       | 252.9  | 177.4    | 57.3                | 487.6   | 30                  |
| Buryatia       | 1018.0       | 272.0  | 308.0    | 250.0               | 830.0   | 81                  |
| Tuva           | 506.0        | 15.6   | 184.6    | no                  | 200.0   | 40                  |
| Khakasia       | 732.0        | 373.3  | 251.0    | no                  | 624.3   | 85                  |
| Zabaikalskii   | 2256.0       | 185.6  | 1024.4   | no                  | 1210.0  | 54                  |
| Total          | 25883.9      | 2896.5 | 6032.1   | 657.9               | 9586.5  | 37                  |
regions and by different researchers, the measured rates are close and vary from a few hundredths of a millimeter on gentle slopes to the first millimeters on steep slopes.

According to research by V.A. Khmelev and A.A. Tanasienko [1] from the cultivated slopes of the Presalairskaya plain for 120 years, approximately 9 cm of the humus-accumulative horizon was washed away. Annually lost soil mass from 1 hectare of weakly washed chernozems and dark gray podzolized soils varies within quite narrow limits - 5.7 to 7.1 tons. On the medium-eroded soils, the washing out varies even more widely - 12.9 to 16.5 tons/ha per year. Annual erosion of soil mass on heavily eroded chernozems exceeds 20 tons/ha. Within the Priobye and Presalairye, where the intensive anthropogenic impact on the soil cover is estimated for dozens of years (after the massive development of virgin and fallow lands), the average annual washout of soils does not exceed 8.1 to 11.6 tons/ha. Simultaneously with the erosive removal of the soil mass during the intensive land use, there are significant losses of humus soils. From each hectare of weakly washed-out soils with solid runoff products 540 kg of this substance have already been washed out. The humus loss in the medium-eroded soils is 2 times higher (approximately 900-1400 kg/ha), some of the washed-out material accumulates on the downslope aprons, forming soils with high humus content, the proportion of such soils is very small (2-3%). In most river basins in the south of Eastern Siberia, the sediment runoff is usually less than 20 tons per km2, the average density of gully dismemberment does not exceed 0.05 km/km2, and the erosion of arable land averages 5-10 tons/ha per year.

Table 2 presents the distribution of zones with different intensity of potential washout for the main agricultural enclaves of the south of Eastern Siberia.

| Washout intensity, t/ha in year | Nazarovskaya depression | Kanskaya depression | Yuzhno-Minusinskaya depression | Irkutsk-Cheremkhovo plain | Tunka Depression | Kuda basin [2] |
|-------------------------------|------------------------|---------------------|--------------------------------|--------------------------|----------------|----------------|
| ≤2                            | 27                     | 52                  | 34                             | 19                       | 30             | 51             |
| 2-5                           | 14                     | 23                  | 27                             | 21                       | 25             | 29             |
| 5-10                          | 28                     | 17                  | 12                             | 45                       | 25             | 15             |
| 10                            | 31                     | 8                   | 27                             | 15                       | 20             | 5              |

Based on the statistical analysis of long-term observation series of the suspended sediments runoff, the basins are identified, which are merged in four regions with different trends in the behavior of erosion processes. The prevailing trend in the first Ob – Yenisei region with a positive trend of atmospheric humidification is an increase in the intensity of erosion processes. It is characteristic for 80% of the basins in the region. In the structure of erosion processes, the role of flash shower increases, as indicated by the positive trends in the erosion index of precipitation.

The second Angara region is characterized by a complex multidirectional nature of the process intensity change. Against the background of the generally downward trend of erosion processes caused by the negative trend of atmospheric humidification and the decrease in water reserves in snow, in some river basins there is a noticeable activation of erosion activity associated with massive felling of forests. The strongest influence of concentrated felling on erosion processes is manifested in felling not older than 2-5 years. If the deforestation occupies 1-5% of the basin area, the suspended sediment runoff module increases by 50-300%, the turbidity of the water increases it by 100-800%. Currently, the volume of wood harvesting in some areas is increasing. In the third Selenga district, covering the basins of Barguzin and Selenga rivers, the descending trend of suspended sediments runoff predominates. The main reason is an abrupt decline in agricultural activities in this area over the past 20-25 years. In some areas of Buryatia, where practically complete closure of agriculture due to socio-economic reasons is noted, the growth rate of gullies, the rate of flat erosion on slopes and the extent of sediment runoff are decreasing. For the fourth region (the Upper Amur basin), the opposite
tendency is characteristic: an increase in the intensity of erosion processes against the background of the progressive growth of atmospheric humidification in the second half of the 20th century. Thus, the revealed positive trends of erosion processes are characteristic for the basins with high process intensity (the Yenisei and Amur basins). Due to the climate change, these trends will become even stronger. The most significant increase in sediment runoff should also be expected in areas of new economic development (development of gold, oil, gas, deforestation, etc.). In this regard, in order to reduce the amount of runoff and improve the ecological situation, we need measures of environmental and geomorphological safety, primarily restoration and creation of new anti-erosion protection systems.

Consider the dynamics of soil degradation in the economic land use in the Selenga river basin in the 20th century. It should be emphasized that this river is the main supplier of pollutants to Lake Baikal in solid and dissolved form. For assessing the influence of anthropogenic disturbance to lands upon the soil erosion rate for the period concerned, we carried out a correlative analysis of the changes in the area of eroded lands depending on the degree of land plowing, and on pasture load. It was found that the area of eroded lands increases directly with an increase in anthropogenic impact on landscapes (figure 1).

For the 20th century the curve of change in the arable land area represents an increase till the late 1980s with two periods of a slight reduction during the war years (the 1920s and 1940s). Also conspicuous are two periods of an abrupt increase in the proportion of plowed-up lands at the time of collectivization when the area of arable land increased by 40%, and during the opening-up of virgin lands. At the period of collectivization, characterized by merging of small fields, owned by peasant, the plowing-up of boundary paths and formation of relatively large tracts of arable lands, as well as by enhancement in mechanical action on the soil, the soil erosion and deflation intensity has increased considerably. An enhancement in the activity of erosion processes during that period was favored by concentrated forest felling. Virgin and fallow lands in Buryatia began to be developed in 1954 to extend over 20 years. For that period the area of arable land in the Republic increased by almost 40%, i.e. from 646 thou ha in 1953 to 1027 thou ha in 1975. Furthermore, the overall size of plowed-up lands exceeded the increase in arable lands in economic turnover. The post-war period till the end of 1980s showed a considerable increase in sheep population, also contributing to an enhancement of basin erosion, which is testified by an increase in sediment discharge of the Selenga river (figure 1). In the event of plowing up large tracts of lands with low humus content, sand and loamy sands were
exposed on the surface, and the first year witnessed the onset of wind and water erosion. For that reason the opening up of virgin lands was often accompanied by the abandoning of old arable lands. At that period, the kolkhozes of the Pribaikal’skii and Zakamenskii districts were abandoned, because of soil degradation, about 90% of arable lands against the area of newly developed lands. The kolkhozes of the Tarbagataiskii district even reduced the overall area of arable lands (they opened up 2.4 thou ha of new lands, but abandoned, as fallow 4 thou ha of plowed fields). During that period, typically with low humidification, deflation was evolving particularly intensely on sandy soils.

An enhancement in deflation was characterized by an expansion of the area occupied by unfixed sands, and by the emergence of new centers of aeolian abrasion. Once again, sands began to encroach onto human settlements, roads, and agricultural lands, which were accompanied by formation of deflation basins. The movement of barkhans averaged 6-8 m/year. Within the Selenga basin, an increased water content and intensive basin erosion were observed in 1959-1973. The subsequent period of high water content, which was observed in 1984-1995, did not show any extreme development of erosion processes, which was reflected on the plot of the difference-integral curve for suspended loads of the Selenga river. (figure 1).

3.2. Soil deflation in Siberia

Active deflation is one of the major problems of soil degradation in southern Siberia. The distribution and intensity of deflation depends on the characteristics of the relief, the wind regime and the presence of the earth's surface without vegetation cover or with sparse vegetation. The flat terrain in Western Kulunda creates favorable aerodynamic conditions for the wind. The presence of wind-impact slopes, gently sloping corridors located along the direction of the prevailing winds in East Kulunda, Minusinskaya depression, on the Irkutsk – Cheremkhovskaya plain, in the Baikal and Transbaikal regions promotes active deflation of plowed surfaces. The area of deflated lands in individual depressions reaches 40%.

Based on experimental research, the intensity of aeolian processes increases from the northern forest-steppe to the steppes and further deserted steppes [3]. With the increase in the deflation intensity, the size of the transferred material increases as well. In the Nazarovskaya forest-steppe, the wind can slightly transfer dust, in the Onon – Argunskaya and Koibal’skaya steppes sand is involved in the transfer. On Lake Baikal in Priol’honye, during the storm winds, gravel and small gravel are moving, periodically by a slip over a distance of 30-40 cm with the strongest gusts of wind.

In the forest-steppe regions aeolian accumulation of substance is dominating, as evidenced by the loess-loamy strata, which are formed by aeolian processes. The rate of aeolian accumulation according to the data of stationary studies varies from 0.01 mm in moderately humid years to 2 mm in extremely dry ones. In the steppes deflation and transport of aeolian material predominate. In the Koibal’skaya, Onon-Argunskaya and Barguzinskaya steppes the deflation rate varies from 0.1 to 2.2 mm/year. In the deserted steppes of Priol’khonye it increases to 3-6 mm/year, in the Peschanha stow to 20-35 mm/year, in the local areas during hurricane winds the catastrophic rates of aeolian denudation reaching 170 mm/year are fixed. The average rate of the areal deflation on sand massifs in the Selenga valley, determined by archaeological data, was 0.6 cm/year for 1000 years, and measured by natural check points 1-8 cm/year [see 3]. In general, the prevailing intensity of deflation in the subarid regions of southern Siberia is 10-50 tons/ha per year. It is close (the same order) with the values of annual soil losses from deflation in the zonal steppes of the East European and West Siberian plains. The dynamics of gully formation is of a pulsating nature, when after several years of almost complete absence of gully peaks growth; their more active growth (1-3 m/year and more) in wet and extremely wet years is noted. It has been established that the most forms of erosion in the last 15-20 years the rate of regressive erosion has decreased to 0.3 m/year. The decrease in the activity of gully formation is explained by the development of a longitudinal equilibrium profile, the use of soil protection measures, and the reduction of arable land. The analysis of the variability of the deflation processes over the past 100 years has revealed a cyclic nature of their course, caused by variations in atmospheric humidity. In the long-term regime of dust storms over the last 30 years of the 20th
century, there were opposite trends in their increase in the eastern regions of the south of Siberia and a
decrease in the west. They are associated with the change of the atmospheric circulation epochs.
Short-period oscillations of deflation processes with small amplitude are characteristic for the western
part of the territory. In the eastern regions, longer cycles with larger amplitude are observed, reaching
a maximum in the Western Transbaikalia. Against the backdrop of these basically antiphase
fluctuations in the intensity of aeolian processes, which are characteristic for individual regions, the
general periods of their intensification are marked, associated with severe droughts that spread almost
to the entire south of Siberia, when the precipitation was 10-20% or more lower than the norm (in the
early 1920s and 1980s). In general, in the south of Siberia, there is a range expansion of deflation by
means of forest-steppe regions.

3.3. Zones of probably aeolian desertification of Subject sites of Siberia

The results of the study enable ranking aeolian processes according to the degree of their danger to the
environment and to divide the semi-arid landscapes into zones with a different level of possible
desertification, the aeolian processes. For this purpose, the probability of the development of processes
with a weak, moderate, high and very high intensity in each of the regions according to the frequency
of dust storms in a year (N) and the complex climate deflation index (C), as well as the module aeolian
migration of matter (A). On the basis of these calculations, six levels of desertification (table 3) and
the corresponding six possible zones of desertification are identified by the ratio of the repeatability of
processes of different intensity (figure 2).

3.4. Soil protection models

Currently there is a further increase in the volume of implementation of agrotechnical erosion control
measures, preconditions are created for a significant curbing of erosion rates. Models of soil
conservation agriculture in the Siberian region have been developed. Thus, the Altai model of water-
defense systems for contour-meliorative agriculture on slopes includes contour-band organization of
crop rotation tracts, a complex of agrotechnical erosion measures, curtains of high-stemmed crops, a
A system of water-retaining and water-guiding hydraulic equipment linked with forest belts and a road network, estuaries and slope storage ponds.

**Table 3.** Probability of desertification of subarid areas of Siberia, calculated on the base of repeatability of dust storms during the year (N), a comprehensive climate index of deflation (C), % and the rate of migration of aeolian matter (A, t/ha/year).

| Desertification degree | Aeolian processes intensity |  |
|------------------------|----------------------------|---|
|                        | weak (N < 3.0; C < 1.5)   | 0.1–1 |
|                        | moderate (N = 3.1–7.0; C = 1.5–3.0) | 1–5 |
|                        | high (N = 7.1–10.0; C = 3.1–5.0) | 5–10 |
|                        | very high (N > 10.0; C > 5.0) | 10–100 |
| I                      | 85                         | 15 |
| II                     | 65                         | 25 |
| III                    | 60                         | 20 |
| IV                     | 35                         | 35 |
| V                      | 30                         | 20 |
| VI                     | 30                         | 10 |

It has been established that the use of autumn subsurface cultivation with preservation of stubble, in contrast to plowing, is accompanied by significant changes in the processes of snow deposition, by rates of spring snowmelt and the meltwater runoff. The presence of stubble contributes to an earlier and better accumulation, a uniform distribution and preservation of snow on the slopes. The Khakass model of prevention and reliable protection of soils from wind erosion includes the use of complex organizational and economic measures, and forest reclamation and agrotechnical soil protection measures [4]. The most important measure of improving the water properties of soils in arid regions of Siberia is irrigation. Remains of primitive irrigation systems of Khakassia, Tyva and Buryatia are 2–2.5 thou years old. In accordance with the Federal Target Program "Development of land melioration in Russian agricultural purpose for 2014-2020", approved by the Russian government, the reconstruction of Tes-Khemskaya, Barlykskaya, Terezinskaya and Chadanskaya irrigation systems is planned to be carried out on an area of 6394 hectares, for which 7.5 million rubles is allocated [5]. For arid conditions of Khakassia and the Kulundinskaya steppe, the strip placement of crops is the main soil protection method, without wide application of which it is impossible to effectively conduct agricultural production. The Baikal model of soil protection from joint manifestations of water and wind erosion is based on measures for the proper organization of the territory, such as: strip placement of crops and fallow lands, low- tillage farming, sowing with special anti-erosion seeders, plowing "across the prevailing winds" and "across the slope," erosion crop rotation, grass planting, rationally limited grazing, creation of protective forest belts and landscapes. For more effective land use in the Baikal region, preference is given to the restoration of disturbed agrolandscapes.

4. **Conclusion**

The most urgent priority today for optimizing land use under forced conservation of agricultural lands and some easing of soil erosion should be considered inventory of deflation- and erosion-hazardous lands based on their mapping and quantitative assessment. In order to implement these measures, it is necessary to coordinate and integrate soil erosion investigations carried out in the institutes of the Siberian Branch of the Russian Academy of Sciences, at universities and other institutions, and also training of relevant specialists. The interdepartmental commission for environmental safety of the Russian Federation, in 1993, considered the need for urgent measures aimed at preventing further degradation of the soil cover as a threat to the country’s national security [6]. It is finally necessary to adopt a law on soil protection at the federal level and at the level of individual subjects of the
Federation. To conserve soils and improve the ecological situation, not only legal and financial-economic measures are needed, but also an understanding of the threat of soil and water degradation for the welfare of the population of Russia.

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