Wind Erosion in Russia: Spreading and Quantitative Assessment

Larionov G. A., E. L. Skidmore and Z. P. Kiryukhina

Introduction

The first mention of dust storms on cultivated land in the southern part of Russia dates from the end the last century, but the earliest events of wind erosion on sandy soil took place in the XIII - XIV centuries when nomadic tribes moved yearly to the North Caucasus sand lands for the winter period due to the absence of snowpack here from the vast terrain of the steppe zone between the Dnepr and the Volga rivers (Trushkovsky, 1959). Due to spreading the area of cultivated land in the dry steppe zone of the European part of Russia, the occurrence of dust storms increased accordingly from the XIX to XX centuries. The last expansion of cultivated land happened in the late nineteen fifties. The significant part of the newly cultivated land was located in areas with extremely strong winds. It was an additional impact to increase the area subjected to wind erosion. At the same time, the agriculture switched from small grain production to row crops that were conducive to wind erosion. For example, in the Karachay-Cirkassian Republic, the area of row crops grew up to 55% in 1968. The occurrence and severity of dust storms in the North Caucasus grew accordingly. There were 5 dust storms before 1930 and its number increased to 29 during the next four decades (Ryabov, 1974). As a result, after 15 years of cropping newly cultivated soils located in the area with strong winds lost as much as 20 to 60% of its upper horizons (Makkaveev at al., 1972). In 1967, the government of the USSR issued the special decree devoted to combating soil erosion. Intensive water and wind erosion studies were started in old and new research institutes and laboratories. The research institutes, along with project institutes, were obliged to design a general sketch of soil erosion control measures. Before long, regional sketches were created but all attempts to bring them together were unsuccessful since the adjacent regions with the same natural and land management condition had different sets of soil erosion control measures because it was based on field survey data which were subjective to a considerable extent. Then it became evident that the planning of soil erosion control measures must be based on quantitative assessment of the wind erosion rate.

Wind Erosion Modelling

The first wind erosion model was developed in the Forest Amelioration Research Institute in Volgograd. It was based on data received from wind tunnel experiments which showed that wind erosion rate was a power function of the difference between wind velocity and its threshold value. The power value is approximately two. It was suggested that it be used for defining the distance between shelter-belts with soil loss caused by 20% probability wind (Dolgilevich, Vasilyev and Sazhin, 1973). The tolerable soil loss value was derived from the age of humus carbon and the depth of A horizon. It varied significantly from 3.6 (chernozem soil) up to 11.3 (podzolic soil) ton/ha per year (Bilgibaev and Dolgilevich, 1970). This model was never implemented for soil conservation purposes in a broad scale.

The Soil Erosion and Channel Processes Research Laboratory of Moscow State University started to study wind erosion in the North Caucasus in 1968. At first, the field survey was widely used. The data collected in the course of the survey is permitted to evaluate the scale of the problem and to find out some of the general regularity of wind erosion pattern. It became evident that a wind erosion model is needed for quantitative assessment of the wind erosion rate. At that time the Wind Erosion Equation (Skidmore, Woodruff, 1968) was a one of the best developed and well provided for soil conservation purposes but it was not used because of the soils in North Caucasus greatly differ by the threshold velocity values. At first two equations derived from sand transport data were used for this purpose. The first one was suggested by Gvozdikov (1962). The basic equation is

$$q = k\,(u^3 - u_0^3) \qquad [1]$$

where q is the sand transport rate per unit width of surface perpendicular to wind direction (kg m^{-1} s^{-1}), k is the transport coefficient (kg m^{-1} s^2), u is the wind velocity at 10 m height (m s^{-1}), u_0 is the threshold velocity (m s^{-1}). The second equation developed by Zakirov (1968) is

$$q = k\,(u_0/u - 1)^3 \qquad [2]$$

where all the terms are the same as in eq. 1. The transport coefficient for the soils was not developed. Thereafter, only the semiquantitative assessment of the wind erosion rate was possible. The results given by eq. 2 needs to be fitted to field data and have a different critical value for soils with the different value of threshold velocity. This is significant evidence that eq. 2 does not reflect the general regularity of wind erosion of soils. Eq. 1 is better fit to the data of the field survey except the marginal zone where the frontiers between slightly and highly eroded soils is very sharp. Eq. 1 contradicts the low of nature, supposing that some part of the total energy of the wind, which has a velocity higher than the threshold value, does not take part in entrainment and transporting soil particles and must be subtracted from whole wind energy.

It seems more reasonable to use the wind erosion description in terms of energy the water erosion model proposes (Larionov, Krasnov, 1990). Then wind erosion index can be calculated as

$$W_i = 10^{-4}\sum u^3_j p_j/[1+10**4(1-u/u_{oj}\ )] \qquad [3]$$

where W_i is the wind erosion index, u_j is the average wind velocity of the j-th velocity class (m/s), p_j is the probability of wind of the j-th velocity class (%), u_{oi} is the value of the i-th threshold wind velocity. The item in square brackets shows the part of instantaneous wind velocity which exceeds the threshold value. If $u/u_{oi} << 1$ it acquires the values which is very close to zero, if $u/u_{oi} >>1$ it became equalled to 1. The map of wind erosion index of the former USSR is shown on the figure 1. It is based on the more than 600 sets of the wether stations. The wind erosion index must be calculated for each month in order to receive the wind erosion index distribution trough the year. The latter has a great importance due to differences in crop-residue cover and snow pack on the main agricultural region of Russia.

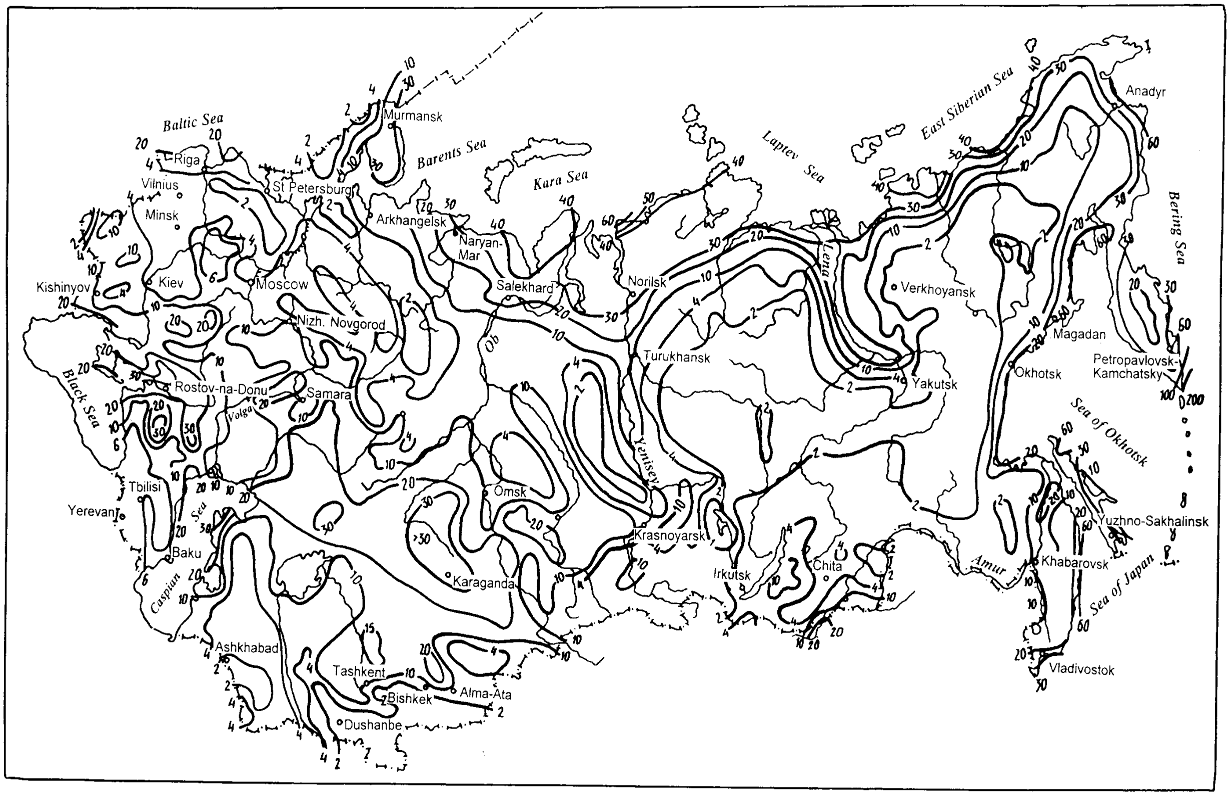

Fig. 1. Average annual values of the wind erosion index (u_o=9 m/s) of the former USSR

The threshold velocity of main groups of Russian soils is well known. It varies from 8 m/s for sandy loam soils up to 14-15 m/s for clay soils. The relative wind erodobility R_e described by jointed formulae of Shiyaty et al. (1971) and Andreichuk (1983) is

$$R_e = 24.7 + 0.9a - 0.3b - 0.4d + 10.1o_m^{0.85}, \qquad [4]$$

where a is the silt (>0.001 mm) content (%), b is the fine sand (0.05-0.25) content (%), c is the coarse sand (> 0.25) content (%), o_m is organic matter content (%). The relative wind erodibility is easily converted into the threshold wind velocity at 10 m height. The threshold wind velocity value is proportional to the relative erodibility if the latter is greater than 50. The threshold velocity is decreased rapidly for soils which erodibility is around forty that corresponds to 9% silt content approximately (Table 1).

Table 1. Relative soil erodibility and threshold velocity of wind

R_e	<15	16-25	26-35	36-50	51-65	66-75	76-85	86-95	>95
Threshold velocity u_o, m/s	6	7	8	9	10	11	12	13	14

There is no data on the protective capacity of crop cover and crop residue at different wind velocities in Russia. Thereafter, the chart from WEQ (Skidmore, Woodruff, 1968) was used for deriving an appropriate equation. The equation has an appearance

$$K_i = W_i\, K_a**(m\, W_i)^{-0.22} \qquad [5]$$

where K_i is the wind erosion crop and management factor for the different values of the wind erosion index, K_a is the wind erosion crop and management factor for the average value of wind erosion index in Russia, W_i is the wind erosion index for i-th threshold velocity, m is the coefficients which equal 1.695, 1.691, 1.673, 1.580, 1.509 for different value of threshold velocity (5, 7, 9, 11, 13 and 15 ms^{-1} correspondingly). The value of K_a is calculated as

$$K_a = 10^{-2}(\sum k_t w_t + k_t k_{sl} w_{sl} + k_t k_{s2} w_{s2}) \qquad [6]$$

where k_t are the wind erosion soil loss ratio correspondingly for 6 period after Wishmeier and Smith (1965), k_{s1} and k_{s2} are the wind erosion soil loss ratio for the winter period with snow pack under and above 10 cm correspondingly, w_1, ... , w_6, w_{s2} are the percent of year value of wind erosion index related to the corresponding period of year. The values of k_t, k_{sl} and k_{s2} are taken from a table of wind erosion soil ratios which is based on the chart after Skidmore and Woodruff (1968). It has a form as analogues table after Wischmeier and Smith (1965) and describes soil protection capacity of small crops, long stem row crops, short stem row crops, perennial grass and leguminous and snow pack (Larionov, 1992).

After that, it is reasonable to suggest that the wind erosion rate, A_w, is proportional to the product of the wind erosion index, W_i, and the crop and management factor, K_i , and can be expressed as:

$$A_w = C\, W_i\, K_i = C\, W_i\, K_a**(m\, W_i)^{-0.22} \qquad [7]$$

where C is the wind erodibility of soil (ton/year per unit of wind erosion index). The comparison of field survey data with those that was predicted by equatuon 7, shows that the soil loss is proportional to the value of the wind erosion index in the region where erosion rate is moderate, high or severe. At the same time, soil loss is significantly overpredicted on the lands which are slightly susceptible to wind erosion. This discrepancy can be caused by two reasons. The first is great fluctuation of the threshold velocity values trough year. After Glazunov (1990), the threshold wind velocity changes two and even more times. The next reason is connected with the avalanche effect which increases wind erosion rate greatly. If the wind velocity is not high enough to move the soil particles which can break down the bigger soil particles and clods, the soil loss is relatively small due to absence of the avalanche effect. In this case, the soil loss is limited by the quantity of loose dust and small particles on the soil surface. In order to take into consideration this phenomena, the equation of logistic curve was used. After that, equation 7 has an appearance

$$Aw = C\, z / (1 + 10^{4.44 - 0.4z}) \qquad [8]$$

where $z = W_i\, K_a**(m\, W_i)^{-0.22}$. The other items are the same.

The long period soil loss data was used for determination of the C coefficient value. The tree sampling point was chosen near weather stations. They are Millerovo, Tikhoretsk and Armavir . They are located in an area with high and severe wind erosion. The comparison of the soil profiles under the shelter belts and in the open field shows that the field top soil horizons are significantly shorter than those under shelter belts. The soil depth differences at the above mentioned points are 14.5, 20.5, 34.0 cm. The age of shelter belts was defined as a quantity of the tree year rings minus 3 (the age of seedlings). The age of shelter belts varied from 33 to 35 years. Then average soil loss equals 55.5, 80.8, 126.1 ton/ha per year, correspondingly. Having the annual soil loss and the value of z (the item in brackets of eq. 8) which equals one if the wind erosion rate is high or severe, it is easy to calculate the value of soil erodibility, C. The erodibility equals 4.92, 4.56, 4.14 ton ha^{-1} $year^{-1}$ per unit of wind erosion index (Larionov, 1992). The soils at chosen points are a silty loam. The humus content is slightly decreased from Millerovo towards Armavir. It can be supposed that the differences in erodibility are to be due to the different humus content. The average value of erodibility equalled 4.5 ton ha^{-1} $year^{-1}$ per unit of wind erosion index and can be accepted as the first approximation for all the loamy soils. The final equation was used for setting up soil erosion map of Russia at the scale 1:1,500,000.

Field Survey and Quantitative Assessment of Wind Erosion

There are a few wind erosion regions on cultivated lands in Russia. They gravitate to southern forestless part of Russia and stretch from the western border of the country to the upper tributaries of the Amur river. The biggest area of severe wind erosion encloses the North Caucasus, the Lower Don and adjacent territories. Due to complexity of relief, different soils and some climatic and synoptic features, it is the most interesting wind erosion region from different points of view. Erosion is caused here by prolonged east or south-east winds which attain storm power when the centre of the Siberian anticyclone moves westward and locates on the western slopes of the Ural Mountains. The North Caucasus is confined by the Caucasus Mountains from the south-west. The Stavropol highland, stretches north-east from the advanced Caucasus ridge to the deep Kuma-Manych depression and divides the described territory into two parts. The south-east part is a dry lowland partly covered by the moving sands and sandy soils. The other part is inclined toward the Sea of Azov and the Cuma-Manych depression. The Don river with its tributaries and the Volga river running to the south deeply dissect northern section of this region. It includes the Azov highland and the Donets ridge at Ukraine.

So when the air mass which ordinarily is colder than the local air moves from Siberia to European part of Russia over the North Caucasus, it is affected by a side constraint from Caucasus mountains and bottom constraint from the Stavropol highland. The speed of the air mass before Stavropol highland and on it’s windward slopes slightly decreases. Wind velocity attains high values on the top of Stavropol highland and increases on the leeward slopes. It can be supposed that wind velocity increasing on leeward slopes is due to gravitational acceleration of the cold air mass. This phenomenon in its extreme manifestation is well known and well described (Alisov, 1947). There is the similar pattern of wind velocity in northern part of the strong and severe wind erosion area.

The more detailed wind velocity distribution on the different part of the windward and leeward slopes and the erosion pattern can be shown on the three profiles crossing the Stavropol highland in its southern part close to the Caucasus mountains , in the central part and at the north-east end. The highest point of the first profile is located on the top of the ridge which separates the watersheds of the Kuma and the Kuban rivers. There is only a week footprint of wind erosion. Further leeward toward the Kuban river valley, the wind erosion rate increases rapidly and attains the maximum value at two-three km distance east from Cirkassk town. Here, behind the shelter belts and under the trees, a significant part of blown soil is deposited in the from of a swell. The swell width and height depends on the wind erosion rate, distance between the shelter belts and its macroporosity as shown on Figure 2.

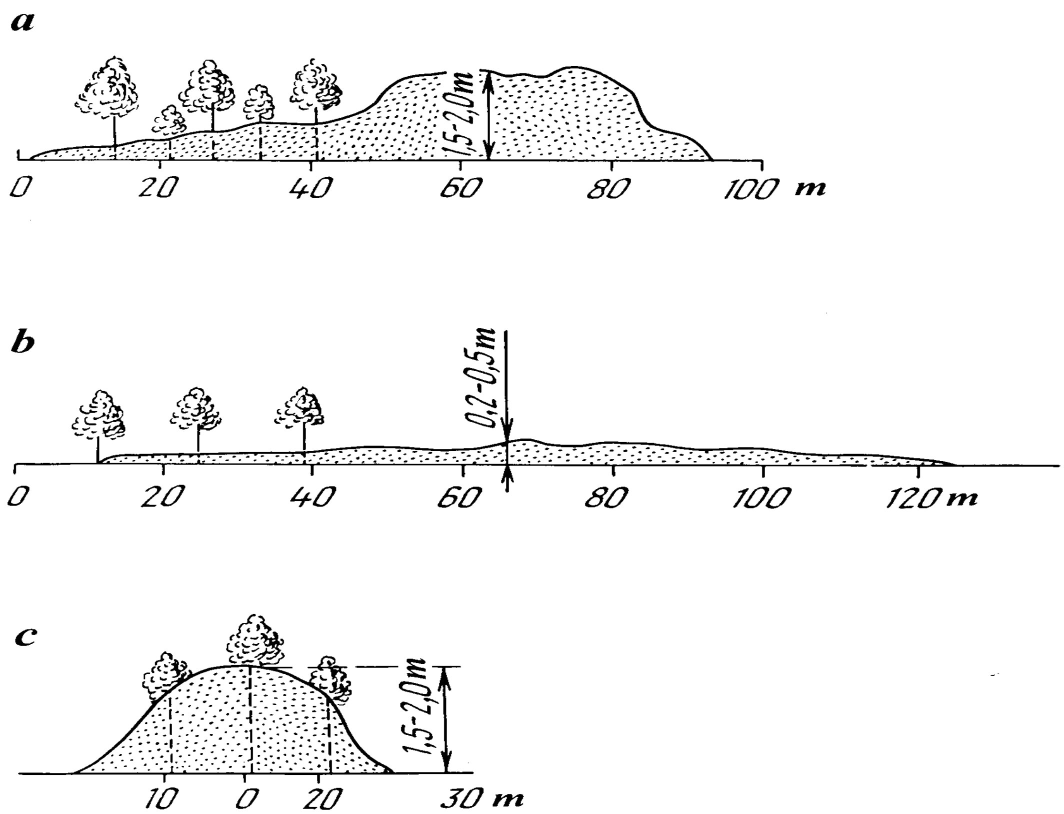

Fig. 2. Soil deposition under and behind the shelter belts of different density. a) The low macroporosity shelter belt, b) The high macroporisity shelter belt, c) The swell in the perpendicular to the direction of erosive wind shelter belt.

The swells in the shelter belt which are parallel to erosive wind direction have a steep sides. In the zone of severe wind erosion, the shelter belts can protect the soil from wind erosion only at distance no more than 10 -12 height of the shelter belts. The distance about 250 - 300 m is enough to attain the wind erosion rate as in open field without the system of the shelter belts. It should be noted that before the shelter belts at distance of 4 -6 height of tree approximately, the soil loss is highest on the whole space between the neighbouring shelter belts (Figure 3).

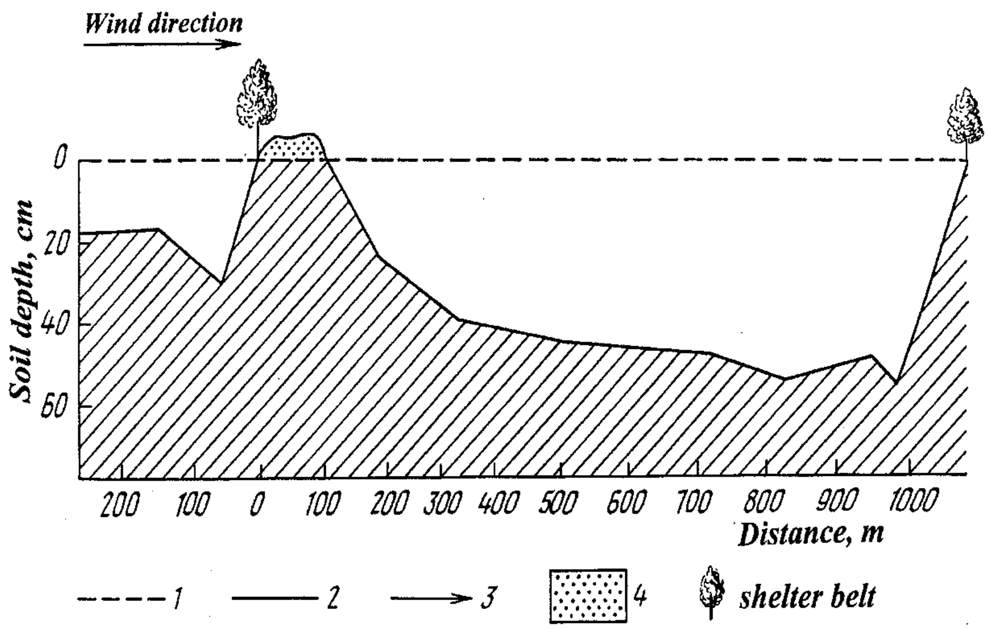

Fig. 3. The soil loss between two shelter belts. 1. The initial soil surface, 2. The soil surface 18 years later, 3. The wind direction, 4. The deposited soil in form of a swell.

Further on the Kuban river terraces, there are no wind erosion footprints even on sandy soils. This part of the Stavropol highland has around 800 mm of precipitation and soil moisture content in winter and spring is equal to the field moisture retention capacity ordinary but high soil moisture content can not diminish the wind erosion rate due to dryness of the arctic air mass. According to calculation during the winter and early spring dust storm of 1969-1970 which lasted 69 hours, the evaporation equals 57 mm. Therefore, the moisture content of more than 50 cm of the soil layer can be dropped from the field capacity up to wilting point (Makkaveev, Larionov, Litvin, 1972).

On the next the lower ridge, which is located between the Kuban river and its tributary the Big Zelenchuk, deposition of wind blown soil material appears only on the upper third of the ridge slope. The wind erosion and its footprints become more distinctive on the top part of the ridge and then the wind erosion rate gradually increases leeward down to the Big Zelenchuk river. The ridge between the Big and Small Zelenchuk, which is lower than the previous two, has the same distribution of wind erosion, but judging from quantity of deposited soil wind erosion rate is less here than on higher ridges.

The second profile crosses the Stavropol highland at its central part. It starts on the small ridge which separates dry lowland from the elevated and more humid northern part of the region. There is no wind erosion on the both windward and leeward slopes. The next ridge is higher that the first one. It is located between Kuma and Kalaus rivers and has an asymmetrical form. The south-east (windward) slope is very steep and long (about 60-80 km). The opposite slope is short and often precipitous. Only the top of this ridge is subjected to wind erosion. The erosion rate can be assessed as high. The next ridge is shorter and higher than previous. The wind erosion here has taken place on the top of ridge. Further to north-west, the height of the terrain increases slightly up to Stavropol city, which is located on the top part of the ridge. There are no evident footprints of wind erosion. The leeward slope starts with a precipice and then becomes less steep towards

Sengiley Water Reservoir. Here is the most severe wind erosion. The wind velocity here is four times greater than near Stavropol city (Ryabov, 1974). The soil particles as great as 4 mm in diameter were found here at the windward part of the swell among the shelter belt trees.

The last profile crossed the lowest north-east part of the Stavropol highland. On this profile, the footprints of wind erosion exist only on top parts of two ridges. Judging from the size of swells behind the shelter belts, the wind erosion here is low or moderate. The deep Kuma-Manych depression elongated from south-east to north-west is close (20-30 km) and parallel to the third profile. There is no wind erosion even on sandy soils. The next to depression is the Ergeny Highland which has asymmetric slopes. The eastern windward slope is short and steep; the western slope is long and gentle. The wind erosion takes place predominantly on the lower south-west part of the latter. The pattern of wind erosion is the same on the other dissected by the river valley part of the described region. It must be noted that the north coast of the Sea of Azov is eroded severely because the air mass attains a great velocity above the smooth water surface. Wind velocity decreases toward the top of the Azov highland and again it attains a high value near Volnovakha town and causes severe wind erosion, but on the leeward slope of the Azov highland, the wind erosion rate decreases rapidly along the slope.

Thus, the mesorelief causes a great impact on wind velocity and as a consequence on the wind erosion rate and wind erosion pattern too. The other factor have no significant influence on wind erosion in this region.

To the south-east from the Stavropol highland on the dry lowland, the wind velocity distribution is rather homogenous so wind erosion pattern is governed by soil properties. Instead of low soil moisture content, sand and sandy soils with clay content under 9% are subject to wind erosion here. Wind erosion pattern on the North Caucasus and on adjacent area is shown on figure 4.

There are other regions of wind erosion in Russia but they are incomparable with the above described. The two relatively small wind erosion spots are located on the eastern and western slopes of the South Ural Mountains. Loamy soil is exposed here to wind erosion. Further to the east, wind erosion has taken place predominantly on sandy and sandy loam soils. In the West Siberia wind erosion expands near salt lake Kulunda, where it is caused by the west winds, and confined by short periods of time, which start after the snow melt and lasts until the spring crop is established. The field survey shows that judging from swells behind the shelter belts the wind erosion rate here is high enough but it can not be compared which the erosion rate in North Caucasus. To the north from the Kulunda lake at the Baraba steep wind erosion has stopped when paraplow soil cultivation has been introduced. The next small spot of wind erosion is located in the Abakan hollow at the upper Yenisey river. Erosion is caused by the mountain valley winds. A few spots of wind erosion exist east from Baikal lake in the Buryat Republic and Chita oblast. Sandy soil is exposed to erosion here which is caused by the east and the north-east winds. On non-cultivated lands, wind erosion can take place only on sandy soils with destroyed vegetation cover.

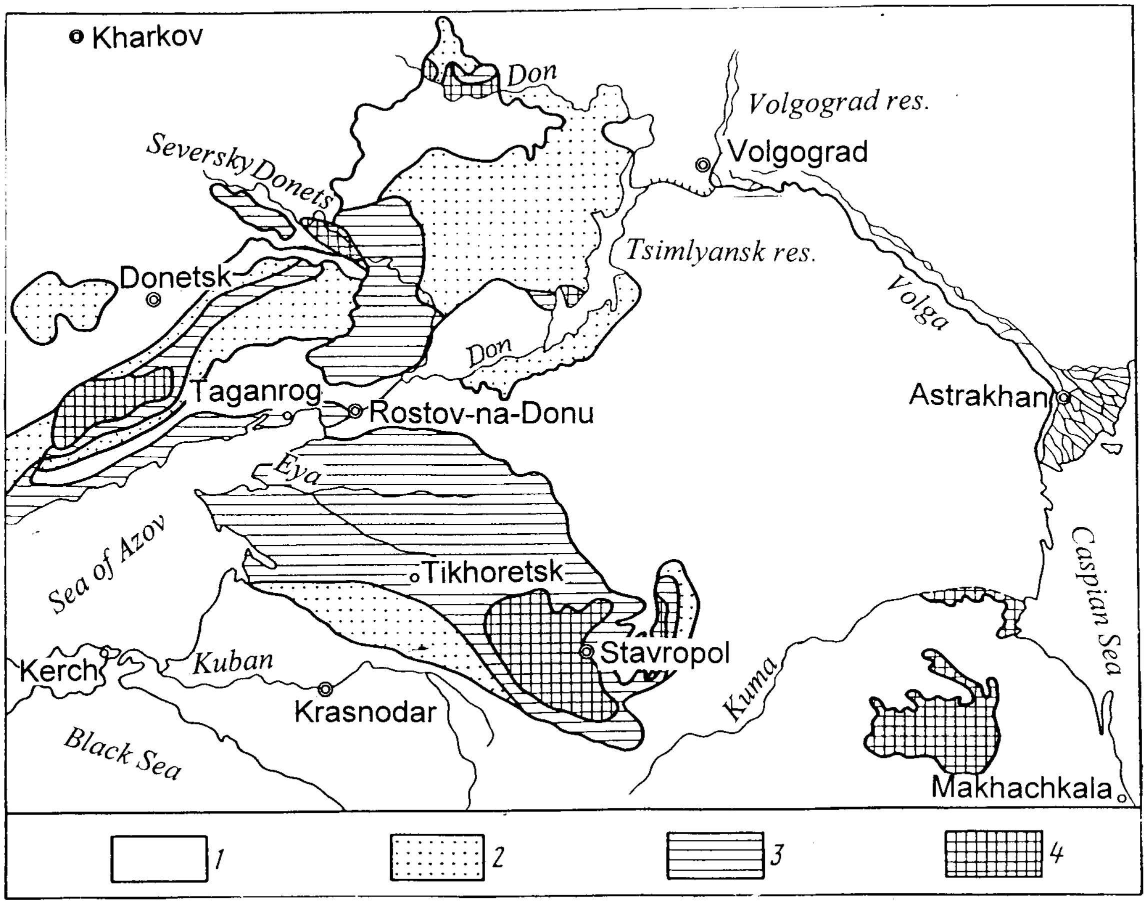

Fig. 4. The wind erosion pattern in the North Caucasus, Lower Don river and adjacent territory. 1. No erosion or very weak, 2. Weak, 3. Moderate, 4. Strong and severe.

The area of cultivated land exposed to different wind erosion rates, total soil loss for four decades (1950 -1990) which results from a long term field surveys and soil erosion mapping based on equation 8 is presented in the table 2 for the main region of wind erosion in Russia.

Table 2. The area of arable land exposed to wind erosion and total soil loss in the south of the European part of Russia for four decades

Administrative region	Wind erosion rate						Total soil loss, 10^6 tons
	slight		strong		severe		
	area, 10^3 ha	soil loss, 10^6 tons	area, 10^3 ha	soil loss, 10^6 tons	area, 10^3 ha	soil loss, 10^6 tons	
Volgograd	315	113	427	615	-	-	728
Krasnodar	359	129	1118	1601	294	917	2647
Rostov	325	122	2465	3967	-	-	3819
Stavropol	980	325	515	741	203	633	1726
Karachay-Circassia	35	12	74	107	28	87	206

The wind erosion caused a lot of damage to soil cover. In some places at Stavropol highland where shallow soils derived from limestone many acres of cultivated land had been excluded from cropping and converted into pasture. During the severe dust storms of 1960 - 1970 many agricultural and civilian objects including irrigation systems, roads, farm buildings and homes were buried or damaged by deposited soil. The surface of the swells behind the shelter belts with low macroporosity were so uneven that a levelling was needed before use of swells for cropping. A significant part of the lost soil is deposited in the form of swells in and behind the shelter belts. It is evident that in an area with dense shelter belts the soil loss is less and the quantity of suspended soil is less, too. In an area with sparse shelter belts and low density of river and gully networks the quantity of suspended soil may reach up to 60% of total soil loss that can cause environmental problem far from the place of dust origin.

Conclusion

Wind erosion in Russia gravitates to the southern forestless zone with strong winds. In the Asian part of Russia predominately sandy and sandy loam soils are exposed to wind erosion. The biggest area of strong and severe wind erosion is located in the European part of Russia. It includes the North Caucasus, Lower Don and adjacent areas including the Eastern part of Ukraine. In this region mesorelief exerts a great influence on wind velocity and thereafter on wind erosion. On leeward slopes of ridges, the wind velocity is increased supposedly due to gravitational acceleration of cold air mass invading a region with warmer air. This phenomena is not studied enough to have a quantitative assessment needed for the wind erosion prediction. Meanwhile, the area with severe and strong wind erosion gravitated predominantly to the top of ridges and its leeward slopes. The soil loss amount in this area is great and damage is of different kinds. The suspended soil material amounts up to 60% of the total soil loss and produces environmental problem far away from the source of dust.

The suggested wind erosion equation presents a new approach in wind erosion modelling.

References

Alisov, B. P.,1947.Climatic regions of the USSR. Moscow. 211p. (In Russian).

Andreychuk, A. L., 1983. Susceptibility of soil to wind erosion and the theoretical aspects of wind erosion control. Doctoral Thesis. Moscow State University. Department of soil science. p. 39(In Russian).

Bilgibaev, M. E., M. I. Dolgilevich, 1970. On the tolerable soil loss rate. IN: Transactions of the All Union Research Forest Amelioration Institute. Issue 1. pp. 239 - 258.(In Russian)

Dolgilevich, M. I., Yu. I, Vasiliyev, A. N. Sazjin, 1973. On the distance between shelter belts on the lands exposed to wend erosion. IN: Newsletter of the All Union Research Forest Amelioration Institute. Issue 12(66). Pp. 11-15 (In Russian).

Gvozdikov, A. V., 1962. Some scientific and managerial aspects of stabilisation of blowing sands. IN: Transactions of the Tashkent Agricultural Institute. Issue 13. pp. 52 - 116(In Russian).

Glazunov, G. P. 1990. Assessment of the threshold velocity for North Caucasian soils. IN: Land and water resources: soil erosion combating and river channel improvement. Moscow state university pub. pp. 164 - 172(In Russian).

Larionov, G. A. 1992. Water and wind erosion of soil: principles and quantitative assessment. Doctoral Thesis, Moscow State University. Department of geography. (In Russian).

Larionov, G. A., Krasnov S. F. 1993. A hydro-physical model of water erosion and it applicability for soil loss prediction. IN: Land and water resources: soil erosion combating and river channel improvement. Moscow state university pub. pp 2 - 15. (In Russian)

Makkaveev, N. I., G. A. Larionov and L. F. Litvin. 1972. Water and wind erosion processes. IN: Land protection from soil erosion and mud flow. Cyrcassk. pp. 66 - 107. (In Russian).

Ryabov, E. I. 1974. The land asks protection. Stavropol. 160 p. (In Russian)

Skidmore, E. L., N. P. Woodruff. 1968. Wind erosion forces in the United States and their use in predicting soil loss. Agric. Handbook N 346. Washington.

Shiyatyi, E. I., A. B. Lavrovskii. 1971. Determination of soil aggregate mechanical stability for wind erosion study. Pochvovedenie, N 12. pp. 146 - 150. (In Russian).

Trushkovsky, A. A. 1959. The stage of overgrowing Terek and Kuma sands. Botanical Journal, Vol. 44. N 5. pp. 128 - 133. (In Russian).

Wischmeier, W. H., D. D. Smith, 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains - Guide for selection of practices for soil and water conservation. Agricultural Handbook No. 282. 48 p.

Zakirov R. S. 1968. Protection of railroad from drifting sands and wind erosion. Doctoral Thesis, Tashkent Transport Institute. Novosibirsk. 24 p. (In Russian).