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Soil erosion and agriculture in the world: an assessment and hydrological implications

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ABSTRACT Data from various areas of the world show that ploughing of virgin lands creates a drastic increase in water erosion of soils. On the average, it can be assumed that after transformation of forest into cropland soil erosion increases by two orders of magnitude and for unforested territories the increase is of one order of magnitude. A special methodology was developed to assess the level of soil erosion in different landscapes and in the world as a whole for pre-agricultural time, the present and the situation when (and if) all suitable land resources would be transformed into cropland. Both the methodology and the results are discussed. The results indicate that soil erosion in the world now is five times more than in pre-agricultural time and could be ten times more if all suitable lands are ploughed. The increased soil erosion leads to an increase in river sediment transport as well as accumulation of the eroded material in river networks. The problem of modification of chemical cycles (the phosphorus cycle in particular) as related to agricultural erosion is also discussed.

BACKGROUND TO THE PROBLEM

The area of cultivated land in the world is 14.3 million km^2 or up to 11% of the ice-free land surface. In some regions of the world cropland occupies the major part of the total area. Seventy one per cent of the area of chernozem (black) soils of the steppes and prairies are now ploughed. In cultivated territories with humid or moderately dry climates, drastic changes in vegetation have occurred and instead of dense or even multi-storey natural vegetation cover, bare soil is exposed for most of the year with sparse crop vegetation existing for a few months.

These changes in vegetation cover are the reason for the very pronounced increase in soil erosion on cropland as compared to natural landscapes. There are many data from various parts of the world proving this statement. There is also much evidence demonstrating the considerably larger sediment loads of those river basins where cropland predominates as compared to neighbouring basins having mainly natural vegetation.

An enormous amount of experimental data was used in the USA to develop the Universal Soil Loss Equation. Based on the latest recommendations (Wischmeier & Smith, 1978) we can indicate the

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following relative values of soil erosion:

Bare tilled soil	*Soil under crops*	*Soil under virgin grass*	*Soil under virgin forest*
1	1-0.1	0.1-0.01	0.001-0.0001

Taking into account the above values as well as the data from different parts of the world one can say that soil erosion on a field is on average two orders of magnitude more than that under a forest and one order of magnitude more than from non-forested landscapes. This conclusion is in fact probably conservative for the differences may be even greater.

The large increase in soil erosion from fields as compared to natural landscapes, and the vast areas of cropland in the world, together point to considerably higher erosion now as compared with the pre-agricultural time. At the present time, about half of potential arable land in the world is cultivated. If this area of cropland grows, the total amount of soil erosion will also increase.

This is the context of the problem discussed in this paper. It is formulated as follows. Taking into account the considerable, often order of magnitude, increase in soil erosion on cropland as compared with natural landscapes and the large area of cultivated lands in the world, there is a need to assess the magnitude of the increase and its spatial distribution according to the principal landscape types of the world.

THE MODEL AND PROCESSING OF BASIC DATA

To solve the problem the following simple model was developed:

$$EG = ERN(AT - AC) + k * ERN * AC \tag{1}$$

where EG is total amount of soil erosion in a given type of landscape, in tonnes per year; ERN is the soil erosion rate under natural vegetation in the given type of landscape, in t km^{-2} per year; AT and AC are the total area of the given type of landscape and the area of cropland, respectively, in km^2; k is a ratio of soil erosion yield from cropland compared to that from natural areas. The first component in equation (1) represents soil erosion from areas with natural vegetation; the second relates to cropland areas.

Data concerning the areas of the principal landscape types in the world and of the main soil types within them have been published by Rozov *et al.* (1978). They also provide data on present cropland areas as well as the expected upper rational limit of the area of cultivated land for each soil type. The data for the landscape types for which the computations have been made are shown in Fig.1 which has been compiled by the author. Corresponding climatic data are also shown. According to Budyko and Grigoriev (Budyko, 1977), the location of natural landscape zones on the globe is determined quite closely by net solar radiation R_n, and annual precipitation P, expressed as an aridity index $R_n\lambda^{-1}P^{-1}$, where R_n is in cal cm^{-2} per year, λ is latent heat of vaporization of precipitation, in cal g^{-1}, P is in g cm^{-2}.

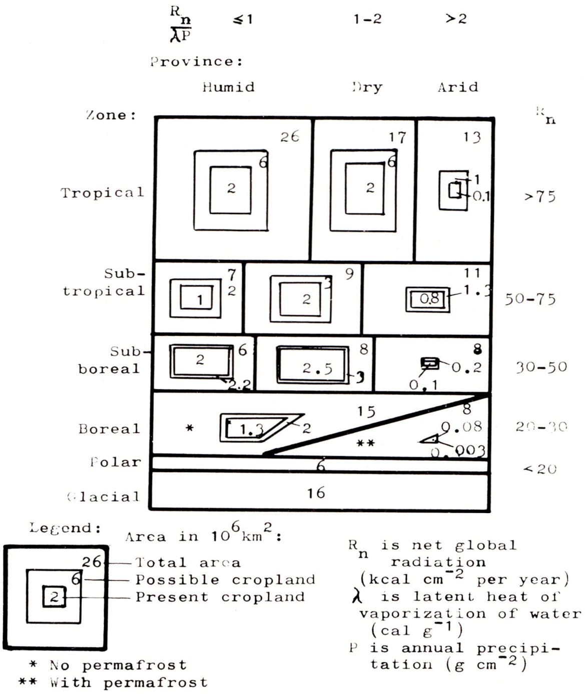

FIG.1 Generalized representation of world land resources according to the principal landscape types.

An an input to the model, a global picture of soil erosion on uncultivated land is required. Such information is not yet available. Therefore, a relationship between specific sediment yield and mean annual air temperature and effective precipitation obtained by Dury (Oliver, 1973) was used as an alternative. The relationship adapted for the purposes of this paper is represented in Fig.2. Effective precipitation, i.e. precipitation minus surface runoff, is represented on the horizontal axis of Fig.2. Mean annual air temperature serves as a parameter. The figure shows that, under the same thermal conditions, soil erosion is minimal where effective precipitation is high (because vegetation is abundant and protects the soil), or low (because the deficit of water prevents detachment of soil particles). This representation has a number of limitations such as the fixed maximum and minimum limits of erosion, but it does

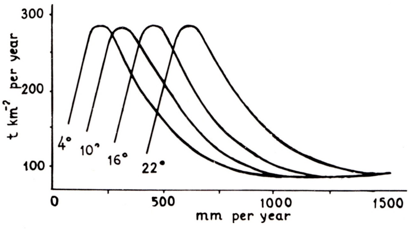

FIG.2 Relationship between sediment yield, annual effective precipitation and mean annual temperature.

provide a generalized picture of sediment yield as a function of climatic parameters.

The next step in the problem's solution involved relating the climatic indices used by Dury to those presented in Fig.1. The relationship of effective precipitation to net solar radiation and the aridity index is shown in Fig.3. This is based on data concerning the detailed structure of the water balance equation for principal landscape zones of the world produced by Lvovitch (1974).

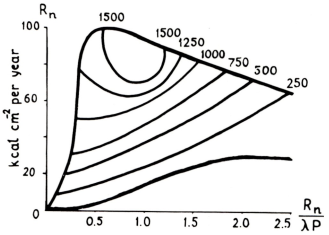

FIG.3 Global picture of effective precipitation (mm year^{-1}).

The relationship of mean annual air temperature (t°) to net solar radiation (R_n) has been obtained using average data for 10 degree latitude bands around the globe (Budyko, 1977, Table I and IV). It is as follows:

$$t^\circ = 0.58R_n - 16 \tag{2}$$

where R_n is in kcal cm^{-2} year^{-1} and t° is in °C.

Using the three relationships developed from the data of Dury, Lvovitch and Budyko, a diagram relating sediment yield to $R_n\lambda^{-1}P^{-1}$ and R_n has been constructed (Fig.4). It demonstrates that the maximum sediment yield lies in dry subtropical areas where the natural vegetation is steppe or prairie. The minimum yields are found in arid areas and in the tundra and coniferous forests zones.

The relationship in Fig.4 is thought to provide a worthwhile representation of the relative distribution of soil erosion yields under natural vegetation throughout the world. However, absolute values of soil erosion rate should have been higher throughout the figure, because only a part of the sediment detached from a slope reaches the river channel.

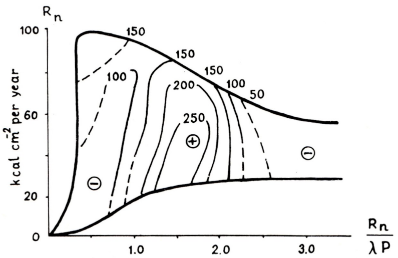

FIG.4 Global picture of sediment yield (t km^{-2} year^{-1}).

The ratio of soil erosion from fields to that under natural vegetation was assumed to be 100 if the virgin landscape was forest and 10 if the natural vegetation was non-forest.

RESULTS OF THE COMPUTATIONS

Computations of soil erosion have been made for 11 of the world landscape types shown in Fig.1 (all except polar and glacial zones). This has been undertaken for three states: first, for the past (when there was no cropland agriculture), secondly, for the present, and thirdly, for the future (when and if all suitable land will be cultivated). For humid landscapes of the tropical, subtropical and subboreal zones as well as for both landscape types of the boreal zone the ratio "k" was taken to be 100; for the other landscape types it was set equal to 10.

Results of the computations are presented in Table 1. It is suggested that the figures obtained are at the lower end of the range of expected real values because of the assumptions made, i.e. first, erosion yields under natural vegetation are probably underestimated; secondly, the ratio "k" was taken at its lower limit; thirdly, the increased magnitude of accelerated soil erosion in mountain areas as a result of cultivation was not considered.

TABLE 1 Assessment of soil erosion in relation to cropland development

Zone	*Province*	*Total (billion t year^{-1})*			*Erosion yield (t km^{-2} year^{-1})*		
		Past	*Present*	*Future*	*Past*	*Present*	*Future*
Tropical	*Humid*	3.9	31.8	92.9	150	1230	3590
	Dry	3.0	6.3	11.9	170	370	690
	Arid	2.0	2.1	3.3	150	160	250
Subtotal		8.9	40.2	108.1	160	710	1920
Subtropical	*Humid*	0.5	11.1	16.7	80	1690	2540
	Dry	1.7	5.6	7.5	200	650	870
	Arid	1.1	1.7	2.2	100	170	200
Subtotal		3.3	18.4	26.4	130	720	1020
Subboreal	*Humid*	0.5	16.6	17.6	80	2760	2930
	Dry	2.1	8.1	9.3	270	1030	1180
	Arid	0.5	0.5	0.6	60	70	80
Subtotal		3.1	25.2	27.5	140	1150	1260
Boreal	*without permafrost*	0.8	7.0	10.5	50	450	680
	with permafrost	0.3	0.3	0.6	30	30	70
Subtotal		1.1	7.3	11.1	40	300	470
World		16.4	91.1	173.1	130	710	1360

DISCUSSION OF THE RESULTS CONCERNING SOIL EROSION

The main conclusions from the analysis presented in Table 1 are as follows:

(a) Water erosion of soils in the world currently amounts to not less than 90 billion t $year^{-1}$. By comparison, global river sediment transport is between 12.7 and 51.1 billion t $year^{-1}$, according to the estimates of nine different authors (*Mirovoi...*, 1974; Lvovitch, 1974), the most probable value being 22 billion tonnes (Lvovitch, 1974).

(b) Soil erosion in the world is currently 5.5 times more than during the pre-agricultural period, and in the future it could increase to 1.9 times as much as at present.

(c) The main reserves of tillable land are in subtropical and tropical zones, and one can expect a considerable increase in erosion in these regions.

(d) Currently, a high increase in erosion occurs in humid regions where the initial vegetation was forest. Deforestation will bring further increases in erosion, particularly in tropical zones where average erosion rates may be 3 times higher than at present and 24 times more than in the pre-agricultural period.

(e) The highest increase in soil erosion occurs in the humid regions of the subboreal zone where erosion has increased 33 times. There, 40% of the lowlands are cultivated, almost all land resources are used, and no considerable increment of soil erosion is expected in the future.

(f) Erosion in the arid provinces is not great because the deficit of water resources predetermines both the small amount of arable land and the low figures of natural erosion.

DISCUSSION OF HYDROLOGICAL IMPLICATIONS

The considerable increase in soil erosion because of agriculture must, apparently, lead to a number of hydrological implications. Leaving aside the well-documented aspects of changes in water regime, other hydrological consequences will be discussed.

River sediment transport should have increased, though to a considerably lesser extent than the soil erosion. Data from the USA (Wischmeier & Smith, 1978) indicate that the sediment delivery ratio is inversely related to the drainage area with an exponent in this relationship of approximately 0.2 for small and medium drainage basins and 0.1 for large river basins. According to the conclusions of Starostina for the Oka River basin, in the central European part of the USSR, deposition of detached soil particles occurs in the following manner: 60% accumulates on the lower parts of the slopes, 20% is deposited in channels without constant water flow, 10% is deposited in small tributaries and only 10% of the detached soil reaches the medium and large rivers (Zaslavsky, 1979). All these figures imply that for large river basins the increase in sediment transport because of agriculture should be an order of magnitude less than the values of soil erosion shown in Table 1. Nevertheless, the magnitude of the river sediment transport increase should be significant, although not uniform over the world.

The increase of river sediment transport may not have been detected by direct measurements which are generally limited to the last few decades. The author has assessed the increase of sediment transport for two rivers in Tennessee and Maryland, USA, by applying available data on land use and soil erosion. In both cases this amounted to 6-7 times more than in pre-agricultural times (Golubev, 1980).

Sediment deposition should have increased in all hierarchical levels of the river network. The lower the level (i.e. the closer it is to a field), the larger is the accumulation. In the southwest Ukraine, the ploughing of virgin lands occurred mostly about 100-150 years ago and Schvebs (1980) indicates that quite considerable sedimentation can be observed in the valleys of small rivers in this region.

The increase in both soil erosion and river sediment transport must accelerate the transport of chemical compounds associated with sediments or adsorbed onto them. Phosphorus is particularly important in this context. Considering the natural range of phosphorus concentrations in the upper soil horizons one can calculate that the global phosphorus transport from slopes associated with sediment measurement is about 50 million t year^{-1}.

Two opposing factors influence sediment-associated phosphorus transport in rivers: deposition of the major part of the sediment before it reaches the river channel and enrichment of river sediments with phosphorus because of its preferential adsorbtion onto fine particles. As a result, sediment-associated phosphorus transport by rivers of the world is several tens of million t year^{-1} and this value is of the same order of magnitude as the annual global production of phosphorus fertilizers. It is clear that the increase in phosphorus transport is one of the main factors influencing the acceleration of the eutrophication process.

Variable increases in agricultural erosion within the world and the non-uniform phosphorus content of the upper layers of the soil should provide a very complicated picture of the increase in phosphorus transport in different landscape types, and, consequently, an intricate picture of the influence of this factor on eutrophication of water bodies.

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