Working Paper

AGRICULTURE AND WATER EROSION OF SOILS: A GLOBAL OUTLOOK

Gennady N. Golubev

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International Institute for Applied Systems Analysis
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PREFACE

The research interests of the Resources and Environment Area span the basic environmental resources--water, air, mineral resources, and land. The existing Tasks within the Area concentrate on certain important aspects of these fields. The Task "Environmental Problems of Agriculture," which is associated with the Food and Agriculture Program as well as the Resources and Environment Area, deals with soil and water-related impacts of agriculture.

Agricultural activity requires from one quarter to one third of the ice-free land surface in the world, and has become a major factor influencing natural resources and the environment. The development of agriculture has caused and will continue to cause both beneficial and detrimental environmental consequences, but more often these effects are unfavorable. At IIASA, the environmental impacts of agriculture are studied at different levels of spatial resolution, from the field to the global level. The impacts are also studied from various time perspectives. This paper assesses changes in soil erosion due to agriculture throughout the world. The time span covered stretches from the preagricultural period to the present, and on to the future, when all arable lands might be cultivated.

AGRICULTURE AND WATER EROSION OF SOILS: A GLOBAL OUTLOOK

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INTRODUCTION

The water erosion of soils is perhaps the most detrimental consequence of agriculture. The transformation of an area with natural vegetation into cropland usually leads to a jump in the rate of soil erosion, and as a result, soil fertility decreases, sediments deteriorate water quality and disrupt the natural course of sedimentation in water bodies, and furthermore, the nutrients transported with sediments also decrease water quality.

In the USSR, soils susceptible to erosion occupy at least 120 million hectares, or about one half of the cropland area of the country. Considerably eroded soils, where yields are 40% that of the normal amount, occupy 5 million hectares (Zaslavsky, 1979). Using both the data of M. Zaslavsky (1979) and data on grain yields in the USSR, we can state that, on a nationwide basis, the fertility of soils used for cereal production has decreased throughout the history of crop production by one quarter of the natural, initial fertility. This reduction in fertility is due to soil erosion.

For the last 200 years in the USA, about one third of the topsoil has washed away and natural productivity decreased by 10-15% (Pimentel, 1979). About 64 percent of the U.S. cropland needs protection from erosion. Soil erosion in the USA presently carries away 46 million tonnes of nutrients (N, P, K) per year, whereas only 18.3 million tonnes of fertilizers (N, P, K) were applied (Crosson and Frederick, 1977). Sediment transport in the U.S. rivers is 3.6 billion tonnes a year, about half of which is ascribed to erosion of agricultural lands ("Control of Water Pollution," 1976).

While the situation of soil erosion and sedimentation in developing countries is not as well studied as in developed countries, it is apparently no better (Eckholm, 1976).

The facts show that agriculture is the major agent responsible for soil erosion. In Table 1, there is data on soil erosion from various terrains in New York State, as compiled from R. Hilliard (1977). These data account for 88% of the state's area. A part of the remaining 12% of the area consists of construction sites (with an area unknown to us), but with the highest specific erosion.

Table 1. Sources of water erosion of soils in New York State.

Land Use Pattern	Area 10^6 ha	Specfic erosion tonnes/ha/yr	Gross erosion million tonnes	Gross erosion percent
Cropland:				
Needing conservation	0.8	16.8	13.4	50
Adequate treatment	1.2	2.8	3.4	13
Pasture	0.6	2.2	1.3	5
Woodland	6.7	(1.0)*	6.7	25
Urban	0.6	3.4	2.0	7
Total	9.9	2.7	26.8	100

*Figure taken by the author.

Cropland areas in New York account for 63 percent of soil erosion, while occupying only 20 percent of the area in question.

In Obion-Forked Deer River Basin, Tennessee, where natural conditions are quite conducive to soil erosion, cropland creates

71 percent of erosion although occupying only 46 percent of the area, (Table 2, data adapted from E. Dyer, 1977).

Table 2. Sources of water erosion of soils in Obion-Forked Deer River Basin, Tennessee.

Land Use Pattern	Area 10^3 ha	Specific erosion, tonnes/ha/yr	Gross erosion	
			million tonnes	percent
Cropland	312	86.4	27.0	71
Grassland	150	5.6	0.8	2
Woodland	136	6.3	0.9	2
Idle	19	4.7	0.1	0
Other*	49	190	9.3	25
Urban	19	4.7	0.1	0
Total	685	11.2	38.2	100

*Gullies, streambanks, roadbanks, leaves, and mines

The reaction of soils to erosion because of the shift from natural vegetation to cropland should be different depending on climatic features, type of soil, pattern of natural vegetation, etc. For example, the countererosive capacity of soil depends on its humus content, carbonates content, and content of cations in the absorbing complex, and mechanic and aggregate composition. Each genetic type of soil has a typical set of parameter values, composed from the list mentioned above. The most erosion-proof soils in the Russian Plain are chernozems, because they have the best set of these parameters. Both north and south of the chernozem zone, the degree of the soil stability against erosion decreases (Zaslavsky, 1979).

N ← declining ← | → declining → S

Podzol ← Sod-Podzol ← Grey Forest ← Chernozem → Chestnut → Sierozem
Soil

Within the chernozem zone, the degree of erosion-proof stability diminishes in the following succession: typical chernozem → leached chernozem → podzolic chernozem → ordinary chernozem → carbonate chernozem → southern chernozem. Similar series exist for other genetic types of soils (Zaslavsky, 1979).

It should be mentioned that the rate of erosion is affected by topography as well as the genetic type of soil. For instance, many chernozem soils of the Russian Plain do not have a topography favorable to soil conservation, and despite the excellent erosion-proof conditions created by the soils' genetic makeup, the rate of erosion can be high.

The principal question discussed in this paper is: what is the present increase in water erosion of soils as compared with preagricultural time, and what can one expect in the future when all suitable lands are used for crops? This question should be answered not only on a global scale, but also for particular sets of natural conditions taking into account differences in soil erosion rates related to differing climate, soil, and topography.

THE MODEL DESCRIPTION

To answer these questions, a simple model was developed:

$$E = b \times E_r^{nat} \times A_{nat} + b \times k \times E_r^{nat} \times A_{agr} \qquad (1)$$

where E is gross soil erosion in a particular type of landscape, in tonnes per year; E_r^{nat} is specific natural soil erosion in a particular type of landscape, in tonnes per sq.km. per year; b is the ratio of natural erosion in mountains compared to natural erosion in lowlands; A_{nat} and A_{agr} are areas of natural vegetation and cropland, respectively, in sq.km.; and k is the ratio of specific soil erosion from cropland compared to that from natural areas.

The first component in the equation (1) represents soil erosion from areas with natural vegetation; the second does so for cropland areas. To make the computations simpler, the equation (1) was transformed into:

$$E = b \times E_r^{nat} \times [A_{tot} + A_{agr} \times (k - 1)] \qquad (2)$$

where A_{tot} is the total area of the territory in question.

A procedure developed to compute the water erosion of soils on the basis of equation (2) is presented as a flow chart in Fig. 1. The following is a discussion of the procedure.

An important input to the model would be the global picture of soil erosion on uncultivated landscapes. Such information has not yet been gathered. Therefore, a relationship of sediment yield dependent on climatic factors (obtained by G. Dury, 1969) was used instead (cited from J. Oliver, 1973). The relationship, adapted for the purposes of this paper, is represented in Fig. 2. Effective precipitation, that is, precipitation minus surface runoff, is represented on the horizontal axis of the figure. Mean annual air temperature serves as a parameter. The figure shows that, under the same thermal conditions, soil water 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 provide an aggregated representation of sediment yield as a function of climatic parameters.

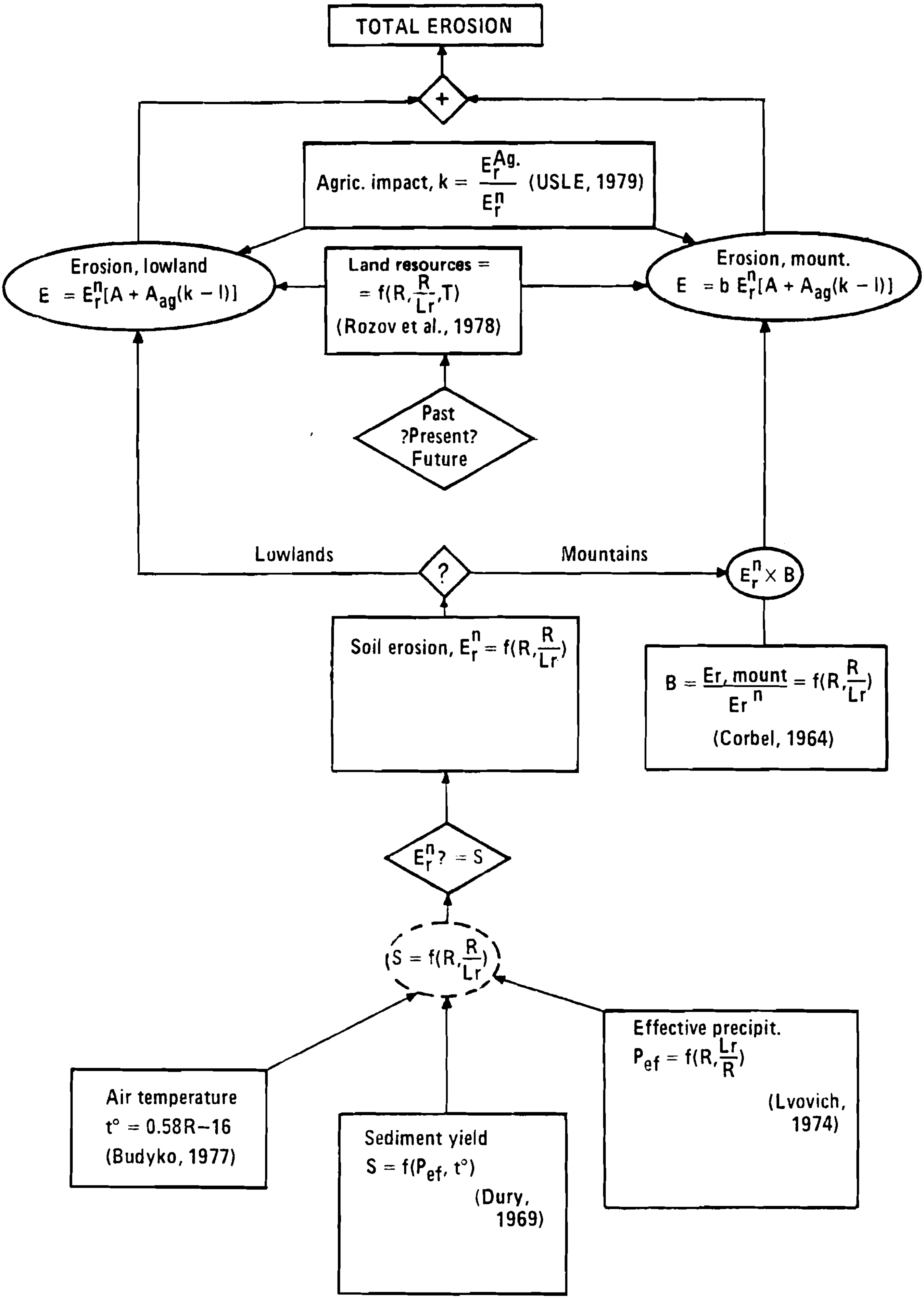
It was discussed in previous publications (Golubev et al., 1978; Golubev, 1980) that the dependence of many natural phenomena on such climatological factors as net solar radiation "R" and precipitation "r" can be shown. Precipitation "r" is expressed in relative terms of the solar energy needed to evaporate it: $\frac{R}{Lr}$. Here L is the latent heat of evaporation. The greater the ratio $\frac{R}{Lr}$, the higher is the degree of aridity in the area in question. A method was developed to represent the content of Fig. 2 in coordinates of R and $\frac{R}{Lr}$.

Effective precipitation P_{ef} as a function of $\frac{R}{Lr}$, R is shown in Fig. 3. The picture was constructed on the basis of the data taken from Table 19 of M. Lvovitch (1974). It was assumed that $P_{ef} = P - R_s = U + E$ where P is precipitation; R_s is surface runoff; U is underground runoff; E is evaporation.

Air temperature t° is described as a function of net solar radiation "R":

$$t° = 0.58R - 16 \quad . \qquad (3)$$

Figure 1. A procedure to compute water erosion of soils.



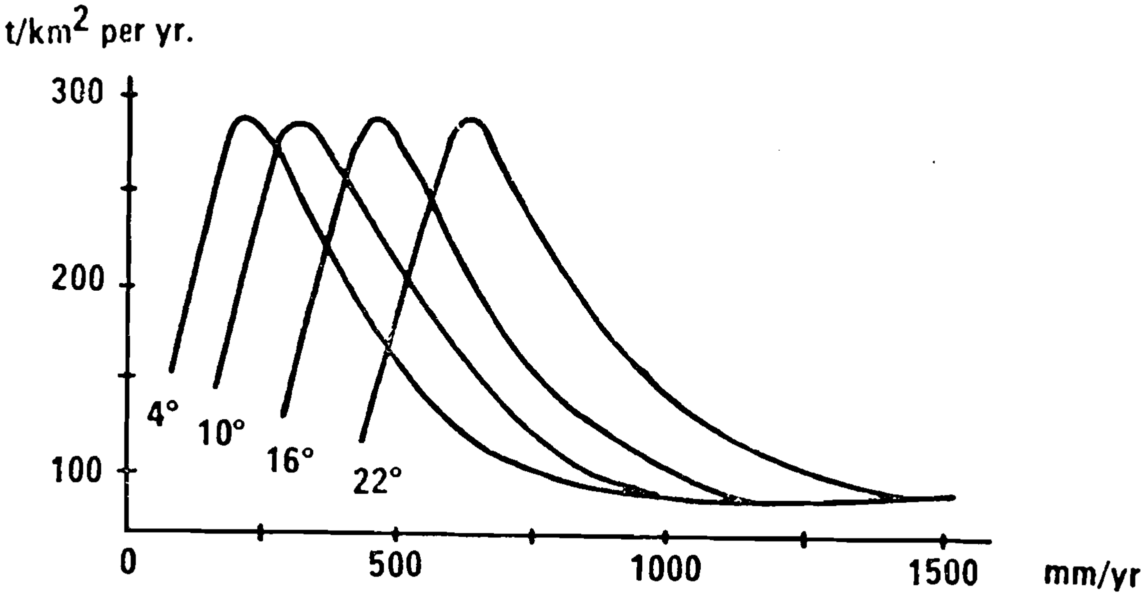


Figure 2. Relation between sediment yield and annual effective precipitation and mean annual air temperature (adapted from G. Dury, 1969).

$$P_{ef} = P - R_s = U + E$$

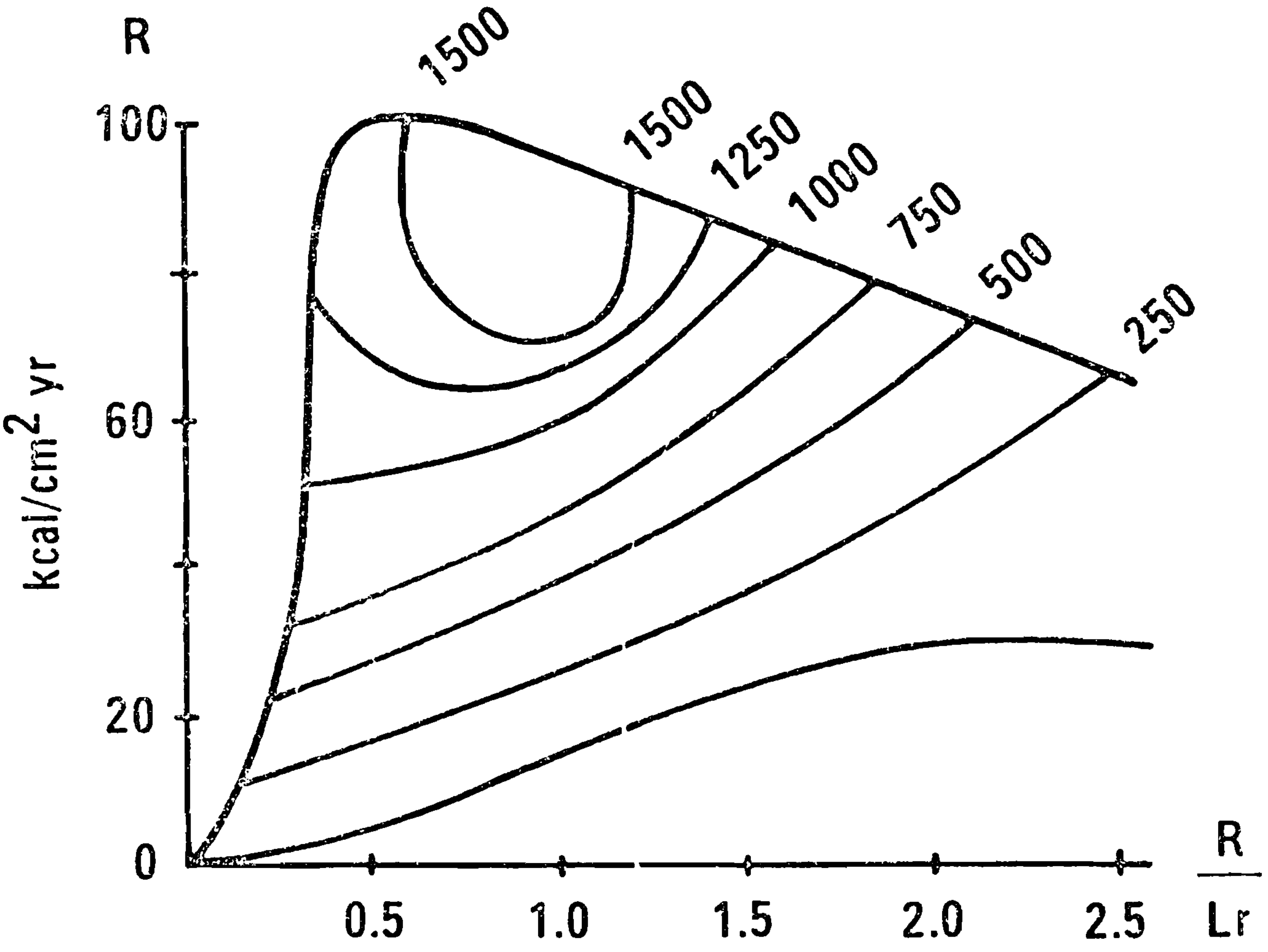


Figure 3. Global picture of effective precipitation, in mm per year.

Mean annual data for the relation (3) were taken for 10 degree latitude bands (Tables I and IV from M. Budyko, 1977).

Next, the picture of sediment yield in relation to $\frac{R}{Lr}$, R was constructed (Fig. 4). Figure 4 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 the temperate forest zone and in arid areas of the world.

After obtaining the global picture of sediment yield, an assumption was made that this picture represents the global picture of water erosion of soils on undisturbed lands. This seems to be the weakest point of the whole approach. A relative distribution of soil erosion is represented quite well, but the absolute figures require some discussion. Behind the assumption discussed here, two main considerations are: 1) For the same area, values of sediment yield should be less compared to soil erosion, if there is a tendency in the relief development to flatten. If the tendency is for the relief to sharpen, the sediment transport should exceed soil erosion. On a global basis, these two tendencies developed in different places partially compensate each other, though the resultant, for the present geologic time, is expected to be in excess of the erosion over the sediment transport. Due to man's activity in watersheds, observed values of sediment yield already contain a certain increment when compared with natural erosion. Because of this, one can expect further compensation of sediment transport in comparison with soil erosion. These very "soft" considerations justify the substitution of data on natural water erosion with that stemming from the measured sediment transport.

Soil erosion in mountainous areas is higher than that in lowlands:

$$b = \frac{E_r^{mount}}{E_r^{nat}} , \qquad \begin{array}{l} b = 1 \text{ for lowlands} \\ b > 1 \text{ for mountains} \end{array}$$

The coefficient "b" was obtained from J. Corbel's data (1964). The values of "b" are presented in Table 3, but they do not seem to be very accurate. Possibly, soil erosion in mountains was underestimated.

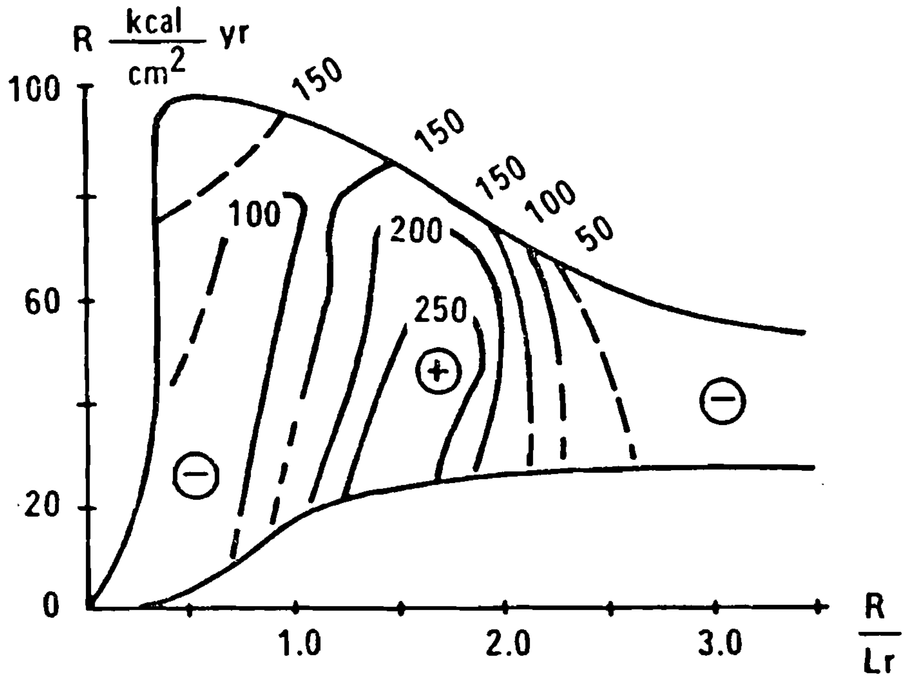


Figure 4. Global picture of sediment yield, in tonnes/km^2 per year.

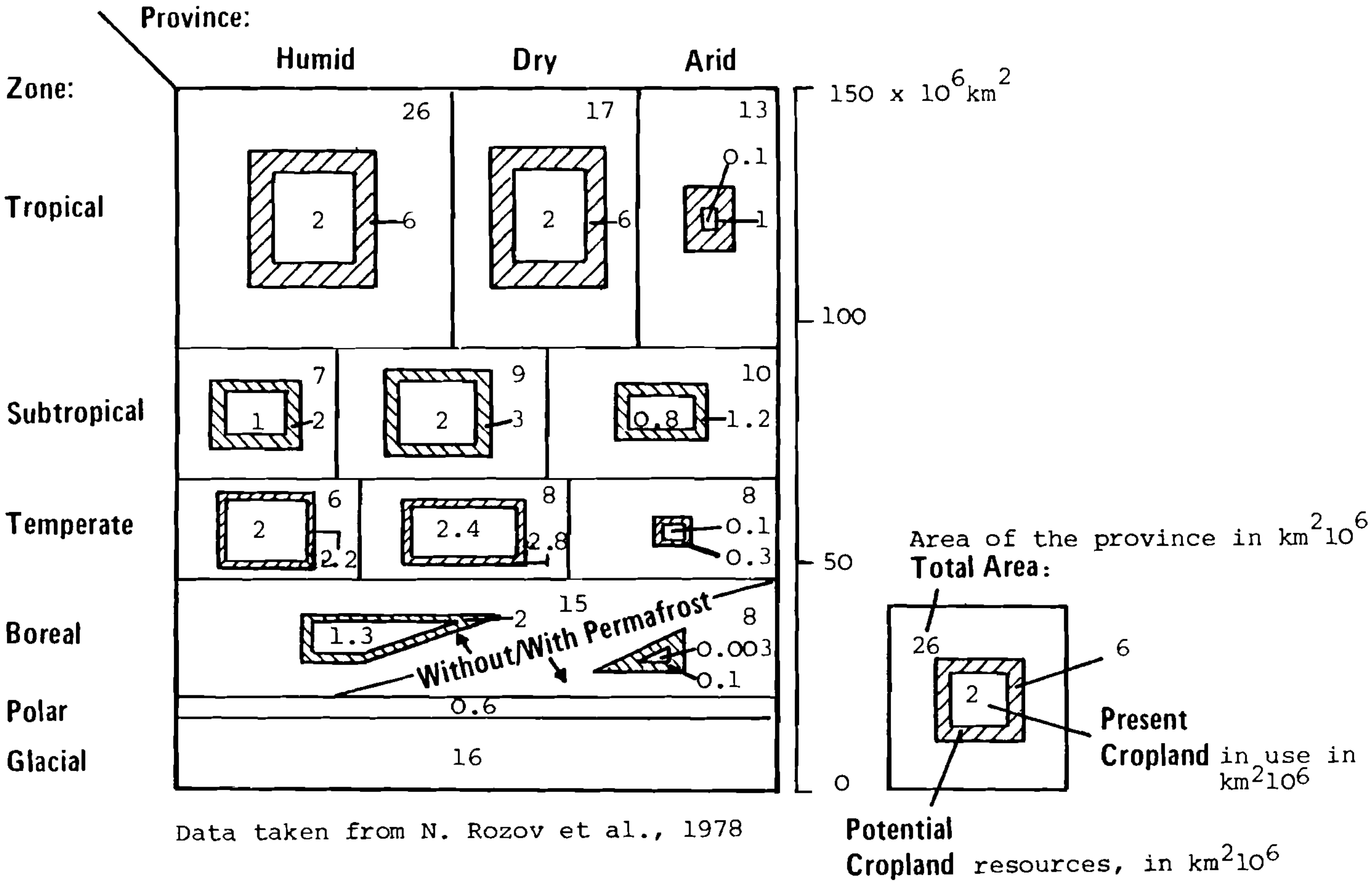
Table 3. Ratio of soil erosion in mountains to that in lowlands.

Climate	Precipitation, mm	$b = \frac{E_r^{mount}}{E_r^{nat}}$	$R, \frac{kcal}{cm^2 yr}$	$\frac{R}{Lr}$
Hot equatorial	<200	2.0	75	6.0
15° N - 15° S	200-1500	2.5	75	1.5
	>1500	2.0	75	0.5
Intertropical	<200	2.0	70	6.0
23.5° N - 15° N	200-1500	2.0	70	1.4
23.5° S - 15° S	>1500	2.0	70	0.6
Extratropical	<200	4.0	65	5.0
t° > 15°	200-1500	5.0	65	1.3
	>1500	3.3	65	0.5
Temperate	<200	5.0	45	3.8
t° = 0° - 13°	200-1500	3.3	45	1.0
	>1500	3.8	45	0.5
Cold	<200	3.3	30	2.5
t° < 0°	200-1500	3.3	30	0.6

A good comprehensive review on the earth's cropland resources has been published by N. Rozov et al. (1978). It provides data for areas covered with various types of soils. For each soil type, the figures are given for total area, area cultivated at present, potential ratios of cultivated lands to the total area, and the expected upper rational limit of an area of cultivated lands. These figures in turn offer the possibility to make the assessments of soil erosion for the past (when there was no cropland agriculture), the present, and the future (when all suitable lands will be cultivated).

The numbers for the soil types are aggregated by Rozov et al. for tropical, subtropical, subboreal, boreal, and polar zones. Within each zone there are aggregated data for humid, dry, and arid provinces. The data are given for lowlands and mountains within each province. Graphic representation of part of this great quantity of information is given in Figure 5.

Figure 5: **WORLD LAND RESOURCES**



Data taken from N. Rozov et al., 1978

Average values of R and $\frac{R}{Lr}$ were added by us to each province (Table 4).

Table 4. Values of net balance of solar radiation R and aridity index $\frac{R}{Lr}$ as related to the land resource areas given by N. Rozov et al. (1978).

Zone	R, $\frac{kcal}{cm^2 yr}$	Province	$\frac{R}{Lr}$
Tropical	>75	Humid	≤ 1
		Dry	1-2
		Arid	>2
Subtropical	50-75	Humid	≤ 1
		Dry	1-2
		Arid	>2
Subboreal	30-50	Humid	≤ 1
		Dry	1-2
		Arid	>2
Boreal	20-30	Forest	0.6-0.8
		Permafrost	0.5-0.7
Polar	<20	-	≤ 0.4

Next we addressed the question of how large the ratio k of specific soil erosion from cropland is compared to that of natural areas. The data from E. Dyer (1977) for Obion-Forked Deer River Basin, Tennessee, indicate that specific erosion rates from cropland are 14 times higher than from woodland. Note that woodland in the area certainly is not virgin. Our calculation of gross erosion for that basin for preagricultural time is based on the assumption that the share of wood and grassland had been 3:1, whereas the specific rates of erosion were actually the same as today (Table 5). Areas designated in Table 2 as "others" were arbitrarily taken at 25% of the present with specific erosion rates at 50% of the present.

Table 5. Sources of soil erosion in preagricultural time in the Obion-Forked Deer River Basin, Tennessee.

Land type pattern	Area 10^3 ha.	Specific erosion tonnes/ha.year	Gross erosion 10^6 tonnes	percent
Woodland	495	6.3	3.1	61
Grassland	165	5.6	0.9	18
Others*	12	95	1.1	21
Total	672	7.6	5.1	100

*gullies, streambanks

At the present time, erosion in the Basin increased by 7.5 times as compared with the preagricultural time. The same index, disregarding various forms of streambank, road, mine, and "other" erosion, is equal to 7.2.

H. Stephens et al. (1977) give data on erosion from various land use patterns in Deer Creek Watershed, Maryland. Average specific soil loss from cropland there is 1870 t/km^2 per year, from pasture, it is 434 t/km^2 per year, while woodland loses 101 t/km^2 per year. We used the same assumptions as in the Tennessee case in calculating soil loss in prehistoric time (Table 6).

The table shows that soil erosion in the watershed has increased 6.3 times.

To arrive at a general value of the ratio "k" by using the recommendations of D.W. Wischmeier and D. Smith (1978) for application of the Universal Soil Loss Equation and aggregating by order of magnitude, the relative rate of soil water erosion is as follows:

Crops	Virgin Grasslands	Virgin Forests
1-0.1	0.1-0.01	0.001-0.0001

After having ploughed virgin forest, soil erosion increases by two orders of magnitude; after ploughing of virgin unforested areas, it increases by one order of magnitude. Natural landscapes which have first been influenced by man's activity and

Table 6. Water erosion of soils in the present and prehistoric periods - Deer Creek Watershed, Maryland.

Sediment Source	Present time			Prehistoric time		
	Area, km^2	Erosion		Area, km^2	Erosion	
		t/km^2yr	t/yr		t/km^2yr	t/yr
Cropland	261.9	1870	489753	-	-	-
Idle	2.2	350	770	-	-	-
Pasture	31.0	434	13454	108	434	46872
Woodland	132.3	101	13362	322	101	32522
Urban	2.6	288	749	-	-	-
Roadbanks	27 km	28 t/km	756	-	-	-
Streambanks	108 km	39 t/km	4212	108 km	39 t/km	4212
Total	430.0	-	523056	430	-	83606

then ploughed, evidence a smaller erosion increment, as was shown previously. Thus, we have:

$$k = \frac{E_r^{agr}}{E_r^{nat}}, \qquad \begin{array}{ll} k = 10^2 & \text{with forest as initial landscape} \\ k = 10^1 & \text{with other landscapes} \end{array}$$

Computations of water erosion of soils for the past, present, and future (see p. 7 for definitions) were made for each province as indicated in Table 4, according to Equation (2) and Figure 1.

DISCUSSION OF THE RESULTS

The results of the computations are presented in Tables 7 and 8.

Table 7. Assessment of water erosion of soils, in billion tonnes per year.

Zone	Province	Lowlands			Mountains			Total		
		Past	Present	Future	Past	Present	Future	Past	Present	Future
Tropical	Humid	2.2	18.0	56.7	0.7	6.6	10.6	2.9	24.6	67.3
	Dry	2.2	4.8	9.3	0.8	1.4	2.2	3.0	6.2	11.5
	Arid	2.4	2.6	4.2	0.3	0.3	0.3	2.7	2.9	4.5
Subtotal		6.8	25.4	70.2	1.8	8.3	13.1	8.6	33.7	83.3
Subtropical	Humid	0.3	8.2	13.8	0.6	6.5	6.5	0.9	14.7	20.3
	Dry	1.1	4.0	5.8	1.2	3.4	3.4	2.3	7.4	9.2
	Arid	0.9	1.4	1.7	0.3	0.5	0.9	1.2	1.9	2.6
Subtotal		2.3	13.6	21.3	2.1	10.4	10.8	4.4	24.0	32.1
Subboreal	Humid	0.3	10.6	11.3	0.6	15.4	15.4	0.9	26.0	26.7
	Dry	1.4	6.4	7.2	1.3	2.0	2.0	2.7	8.4	9.2
	Arid	0.3	0.4	0.5	1.0	1.0	1.0	1.3	1.4	1.5
Subtotal		2.0	17.4	19.0	2.9	18.4	18.4	4.9	35.8	37.4
Boreal	Forest	0.6	6.5	10.0	0.6	0.6	2.0	1.2	7.1	12.0
	Permafrost	0.1	0.1	0.4	0.4	0.4	0.4	0.5	0.5	0.8
Subtotal		0.7	6.6	10.4	1.0	1.0	2.4	1.7	7.6	12.8
Polar		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
World		11.8	63.0	120.9	7.8	38.1	44.7	19.6	101.1	165.6

Table 8. Assessment of water erosion of soils, in tonnes per sq. km. per year.

Zone	Province	Lowlands			Mountains			Total		
		Past	Present	Future	Past	Present	Future	Past	Present	Future
Tropical	Humid	100	810	2540	190	1840	2950	110	950	2600
	Dry	150	330	640	280	500	780	170	360	660
	Arid	200	210	340	360	360	360	210	220	350
	Subtotal	140	520	1430	250	1150	1810	150	600	1480
Subtropical	Humid	80	2220	3730	210	2280	2280	140	2240	3100
	Dry	200	720	1040	390	1120	1120	270	860	1070
	Arid	100	160	190	190	310	560	110	180	250
	Subtotal	130	750	1170	280	1380	1440	170	930	1250
Subboreal	Humid	80	2930	3120	250	6440	6440	150	4330	4440
	Dry	220	1020	1140	790	1220	1220	340	1060	1160
	Arid	60	90	110	300	300	300	160	180	190
	Subtotal	140	1200	1310	390	2500	2500	220	1640	1710
Boreal	Forest	50	560	860	160	160	540	80	460	780
	Permafrost	30	30	100	90	90	90	60	60	100
	Subtotal	40	420	660	120	120	300	70	320	540
World		120	620	1180	250	1220	1430	150	760	1240

In reading the results, one should keep in mind the approximate character of the numbers. More precisely, they are expected to be relative values. The next general observation is that the data of Tables 7 and 8 and the expression "soil erosion" used in discussing the tables, refer to water erosion of natural landscapes plus agricultural erosion, and thus, do not represent total water erosion. With this in mind, the main conclusions drawn from Tables 7 and 8 are as follows:

1. Water erosion in the world is presently 100 billion tonnes per year. By comparison, river sediment transport in the world is between 12.7 and 51.1 billion tonnes per year, or between 100 and 380 t/km^2yr, according to

the estimation of nine different authors (Kovda, 1977; Lvovitch, 1974).

2. Soil erosion in the world is 5 times more than during the preagricultural period, and in the future could be 1.7 times as much as in the present. This means that at the global level, soil erosion is a problem of the present, more than of the future.
3. The main reserves of tillable land are in subtropical and tropical provinces, and it is there one can expect a considerable increase in erosion. The concerns expressed in the literature about the rise in soil erosion in tropical countries are proven by this global assessment.
4. Presently, the highest increment of erosion is in humid regions. This is due to two causes: a) the transformation of virgin forest typical of these areas into arable land caused an increase in erosion by two orders of magnitude; b) the percentage of area used for crop production is high, reaching 40% in the lowlands of the subboreal zone. Soil erosion there increased 35 times, and naturally, much attention is now devoted to soil erosion in the literature of developed countries situated mostly in the subboreal zone. At the same time, almost all land resources there are used, and since gross erosion will not increase more than at present, the most attention should therefore be focused on reducing current erosion rates.
5. 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. However, specific erosion on cropland there can be quite high, something which is not reflected in the present tables.
6. Because of only modest development of crop production in mountainous areas, the proportionate amount of erosion (compared to total erosion in the world) occurring in mountains is decreasing. It seems, however, that

absolute values of soil erosion in mountains (mainly natural erosion) are relatively small compared to real ones.

As a general comment, it should be mentioned once again that what is of most interest in this paper are the methodology and the relative comparison of the numbers in the tables. The absolute numerical vlaues in the tables are approximate, and hence of less importance.

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