The following acronyms are used in this book. Refer to this list to identify them.

CIAT = International Center for Tropical Agriculture, Columbia
CIDIAT = Center for International Studies of Land and Water, Venezuela
CIP = International Potato Center, Peru
CIMMYT = International Maize and Wheat Improvement Centre, Mexico
CPAC = Center of Agricultural Research of the Cerrados, Brazil
CPATU = Center of Humid Tropical Agricultural Research, Brazil
EMBRAPA = Brazilian Agricultural Research Corporation
ICA = Colombian Agricultural Institute
ICRISAT = International Centre for Research in the Semi Arid Tropics, India
IITA = International Institute for Tropical Agriculture, Nigeria
INIPA = National Institute of Agricultural Research and Extension, Peru
IRRI = International Rice Research Institute, Philippines
IVITA = Veterinary Research Institute for the Tropics and Highlands, Peru
UEPAE = State Research Execution Unit, Brazil

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Chapter 1

Rainfall Erosion in the Tropics: A State-of-the-Art[1]

S. A. EL-SWAIFY AND E. W. DANGLER[2]

INTRODUCTION

Quantitative determinations of the extent and impact of soil erosion by water in tropical regions have been sketchy. However, all available evidence indicates that accelerated erosion is a problem of serious magnitude and with a multitude of detrimental impacts in many tropical countries. Fortunately, in some countries, the problem has yet to reach a critical stage. Data necessary to formulate soil loss tolerances and to quantify the causative parameters of erosional processes in tropical environments are also rare. Concerted efforts are needed in all these directions to acquire necessary data and to evaluate the applicability of existing technological alternatives for erosion prediction and control in these environments. In addition, there are great needs to increase the cadre of technically trained personnel, to emphasize the socio-economic aspects of problem solving, and to enhance the awareness of leaders and policymakers as to the importance of the problem.

Population densities throughout the developing world, particularly in the tropics and subtropics, are increasing at such rates (United Nations, 1977) that the loss or degradation of soil resources in any form should not

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be tolerated. Recognizing this fact, the Food and Agricultural Organization of the United Nations has embarked on a major effort to assess the global extent of existing and potential soil degradation problems (Dudal, 1979). That effort, soon to be completed, will result in the construction of small-scale maps (1:500,000) which will provide an overview of all forms of soil degradation. Over the years, beginning with Jacks and Whyte (1939) there have been several dramatic publications pointing to the ever-increasing pace at which natural resources, particularly land, are exploited, and often destructively diminished, by man. Among the recent accounts of this problem are impressive books by Eckholm (1976) and Brown (1978).

Soil erosion is perhaps the most serious form of land degradation throughout the world. Even in the United States, and after more than 40 years of intensive research, the problem still persists and recent information indicate that soil loss rates may indeed again be on the rise (Carter, 1977). For the tropics specifically, while it is generally acknowledged that erosion is more serious than elsewhere, no analytical or systematic studies have been undertaken to document the problem, its consequences, or potential solutions. The small-scale maps referred to above will not provide the site-specific details necessary for accurate documentation. Other available publications on the alarming resource crisis do not address erosion problems alone or emphasize the tropics. Therefore, the need still exists for an impartial documentation and synthesis by scientists engaged in this area. To examine the rainfall erosion problem analytically, we embarked on the preparation of a state-of-the-art report under the sponsorship of the U.S. Agency for International Development (El-Swaify et al., 1979). Portions of that report form the basis for this paper which will specifically address the extent, impact, and causative factors of rainfall erosion in the tropics. Other sections of the report, not included here, cover erosion control measures, research priorities based on identified knowledge gaps, and the information sources tapped for the different components of the report. Due to time and space limitations, wind erosion, while also recognized to be a serious problem in the drier tropical climates, has not been included.

FORMS AND EXTENT

All known forms of water-induced erosion have been reported to occur in the tropics (Hudson, 1971). These include geologic (natural, normal), or accelerated erosion in such forms as sheet (inter-rill), rill, gully, tunnel, pedestal, pinnacle, puddle, vertical (argillic migration), streambank, valley trenching, and landslides. Opinions differ on which forms are most serious. Most authors agree, however, that from the agricultural viewpoint insidious rill and inter-rill erosion represent the most sustained, though perhaps least spectacular, damage in comparison with such forms as gully or landslide formations (Food and Agricultural Organization of the United Nations, 1977).

Limits of "Tolerable" Erosion

In assessing whether or not ongoing erosion represents a serious problem, the question always arises as to the amount of soil loss which is "normal" and can, therefore, be "tolerated". This question has not been answered in the tropics. Even as recently as now (Young, 1979), U.S. workers still accept figures of annual soil loss that are in the neighborhood of those first proposed by Bennett (1939). These range up to 11 metric tons/ha and assume that top soil renewal in cultivated lands occurs at the accelerated rate of 1 cm/30 years. This rate seems excessive as more recent evaluations indicate a likely rate of 1 cm/60 to 300 years. The Soil Conservation Service, USDA, adopts different tolerance guidelines to suit different prevailing soils and their productivities to important crops in different states. A recent symposium held by the American Society of Agronomy (at the annual society meetings, Ft. Collins, Colo., August 1979) has addressed this question. The complex nature of the problem was brought out by various authors who addressed the separate criteria associated with the determination of soil loss tolerances. These are soil formation rates, soil productivity, and the impact of delivered erosional sediments and associated chemicals on surface water quality. Certain special considerations must be emphasized in formulating erosion loss tolerance for tropical soils. These include:

a. The extreme variability among soils which may necessitate formulation of many different tolerance limits.
b. Even for "typical" soils (e.g., Oxisols), the characteristically high weathering (regeneration) rates are probably more than off-set by the low initial nutrient content, and the fact that subsurface horizons are often characterized by high acidity and unfavorable structure or indurated layers.
c. The unusually high turbidities caused by specific concentrations of erosional sediments from oxidic soils and subsequent impact on the quality of destination water bodies (Ekern, 1977).
d. The very limited resources available to the typical subsistence farmers in developing tropical countries for correcting the detrimental effects of erosion.

On one hand, these combined factors suggest that soil loss tolerance limits for tropical soils should be lower than their temperate counterparts. On the other hand, realistic determinations of tolerance limits must consider the socio-economic elements pertinent to a specific environment; population pressures may modify the "technically feasible" tolerances upward.

Methodological Considerations

Information on erosion extent was obtained from such a large number and variety of sources that the retrieved data lacked uniformity. Soil loss information was reported as actual data or potential (hazard) esti-

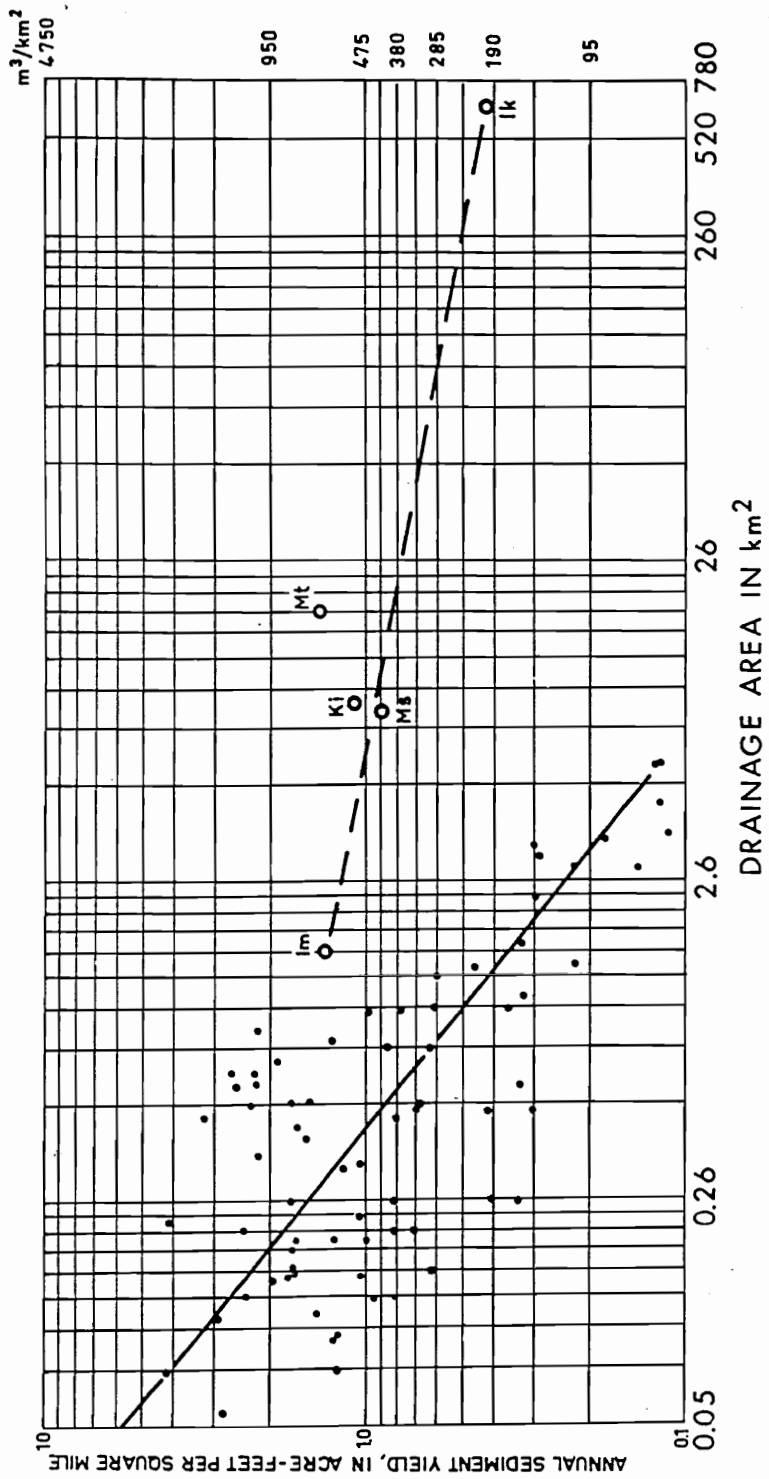

Fig. 1. Relation of mean annual sediment yield to drainage area for five catchment basins in Tanzania (open circles) compared to 73 basins (dots) in eastern Wyoming, USA (Rapp, 1977b).

mates and were qualitative (severity) or quantitative (metric ton/ha). Procedures upon which these were based included remote sensing or site observations, at a scale which is large (based on defined plots), intermediate (small catchments), or small (whole river basins or continents). Another major methodological aspect was the need to emphasize the distinction between actual soil loss data and sediment delivery data (Roehl, 1962). Often, sediment loads of rivers were the only data available. Figure 1 shows some of the few available correlations in the tropics between soil loss and sediment delivery for catchments of different sizes. It shows a considerably smaller reduction in sediment delivery than for a U.S. site. However, it must be acknowledged that such a relationship also reflects other characteristics of the catchment aside from land area. Perhaps most important among these is added effects of catchment relief characteristics. In general, existing data indicate, as in Fig. 1, that specific field soil losses generally exceed sediment delivery (due to redeposition of eroded sediment in areas of flat topography within the drainage basin). However, Heusch (1981) pointed out possible reversals of this trend when gully formations prevail as the major cause of erosion in a particular setting.

General and Specific Inventory of Rainfall Erosion

An examination of general trends for rainfall erosion reveals that most rainfall erosion is restricted to the regions between 40°N and S Lat (Constantinesco, 1974). Figure 2 shows the widely variable climatic regions within the tropical zone (Troll, 1966). As expected, by virtue of limited rainfall, the arid tropics have low actual or potential erosion. On the other hand, erosional trends in the humid tropics are quite dependent on the extent of disturbance by man. Thus, lands in these regions display low actual erosion by water if the effective natural protection provided by abundant vegetation is undisturbed. However, the erosion potential in such regions is severe and will be manifested upon disturbance of vegetation because of aggressive rainfall characteristics. It is the semi-arid tropics that represent highly variable and unpredictable trends. Generally, these areas are in constant danger of being only sparsely vegetated at the end of the dry season and therefore possess little protection against rainfall erosion at the onset of the rainy season (Rapp, 1977a). Furthermore, it has been shown that soils prevailing in these regions are more susceptible to erosion than the highly weathered soils of the humid tropics (El-Swaify and Dangler, 1977, see Fig. 3).

Table 1 shows that Asia undergoes the most active erosion of all the continents. Further examination of sediment loads in specific rivers not only confirms this picture (Table 2), but also shows that rivers in India are particularly burdened by high sediment removal rates. The overall rates reported in this table may be misleading due to the very site-specific nature of erosional processes, whereby a small percentage of a drainage basin can contribute a large proportion of the erosional sediments.

Analytical accounts of erosional trends and hazards in the tropics with view of causative factors are nearly absent in the published litera-

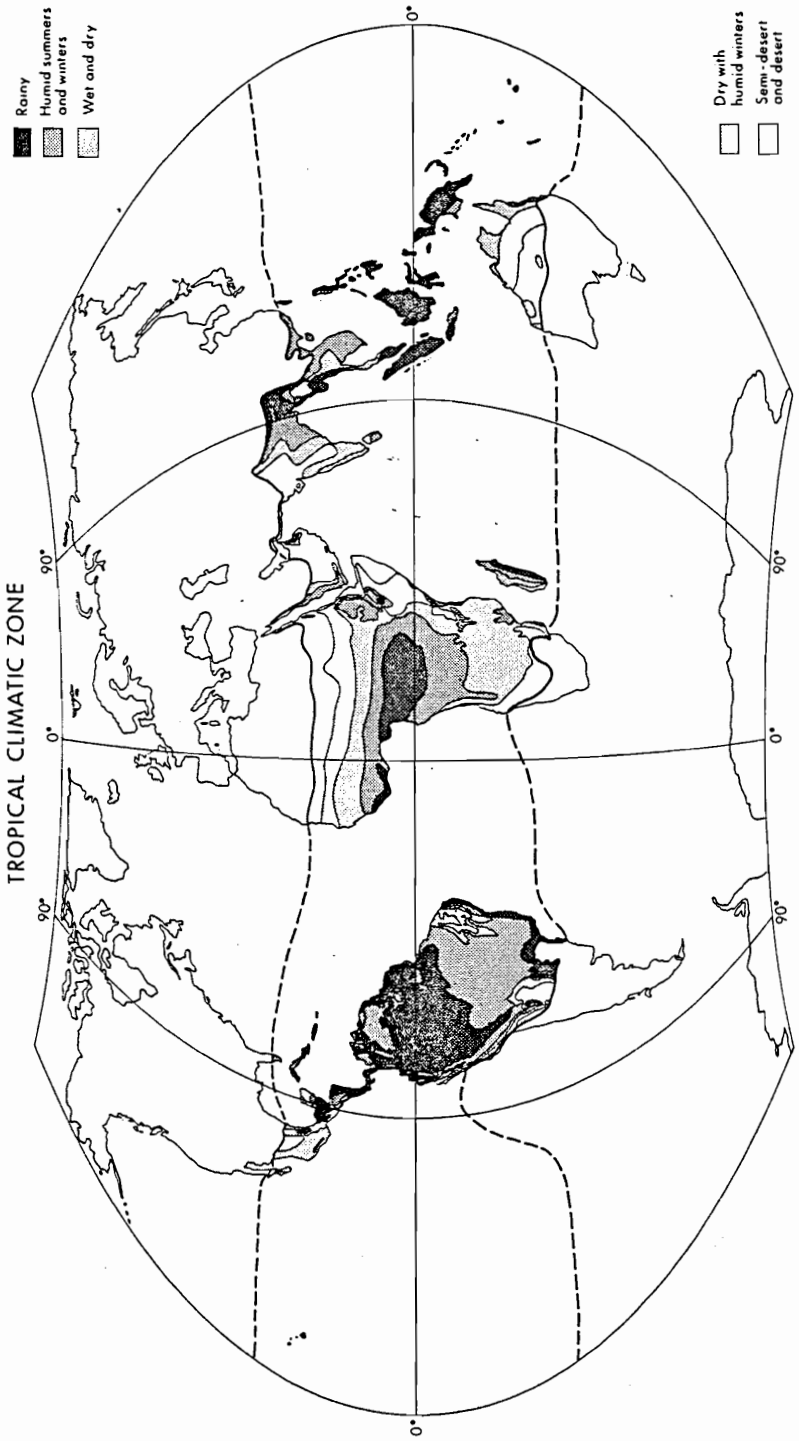

Fig. 2. Subclimatic regions within the tropical zone according to Troll (1966).

Table 1. Rates of erosion of the continents.†

Continent	Area	Mechanical denudation rates
	10^6 km²	metric tons/km²/year
Africa	29.81	47.0
Asia	44.89	166.0
Australia	7.96	32.1
Europe	9.67	43.0
North and Central America	20.44	73.0
South America	17.98	93.0

† Modified from suspended river sediment data. Source: Strakhov (1967) in Chorley (1969).

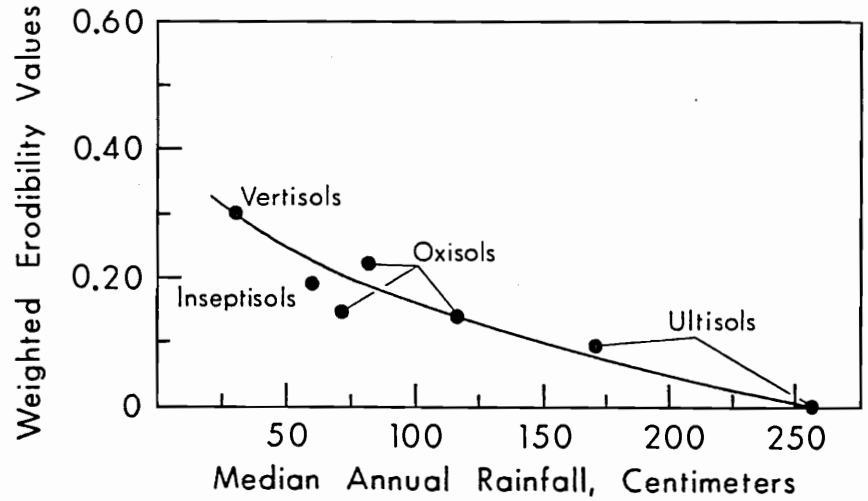

Fig. 3—Erodibility values for different residual soils on Oahu, Hawaii as a function of annual rainfall prevailing at the site where the soil was formed.

ture. Fournier (1962) utilized empirical indices of rainfall aggressivity and topographic setting and their correlations with sediment loads of rivers to construct a map of rainfall erosion hazards in Africa, south of the Sahara (Fig. 4). His hazard classes corresponded to erosion losses of 0.4–2.0, 2.0–6.0, 6.0–10.0, 10.0–15.0, 15.0–20.0, and above 20 metric tons/ha/year, respectively. As noted in the map, most tropical Africa lies in higher risk classes, namely 10.0 metric tons/ha/year or more. Although soil classification was projected on his map, that information was not applied in developing the various hazard classes, nor were vegetation type or distribution of prevailing land use patterns considered in the map's construction. Other scattered data and descriptive accounts indicate that severe erosion incidences occur in the following countries of tropical Africa: Swaziland, Uganda, Ivory Coast, Basutoland (Lesotho), Ethiopia, Ghana, Somalia, Upper Volta, Botswana, Senegal, Niger, Madagascar, Gambia, Nigeria, Zimbabwe, Guinea, Chad, Kenya (Highlands), Sierra-Leone, Liberia, Cameroon, Tanzania, Mali, Gabon, and

Table 2. Estimated annual soil erosion within drainage basins of selected rivers of the tropics.

River	Drainage basin area (10^3 km^2) and countries	Average annual-suspended load	Estimated annual soil erosion from field†
		metric tons × 10^6	metric tons/ha
Congo	4,014 (Several)	65	3
Niger	1,114 (Several)	5	0.8
Nile	2,978 (Several)	111	8
Chao Phraya	106 (Thailand)	11	21
Irrawaddy	430 (Burma)	299	139
Damodar	20 (India)	28	284
Ganges	1,076 (India)	1,455	270
Kosi	62 (India)	172	555
Mahanadi	132 (India)	62	93
Mekong	795 (Several)	170	43
Red	120 (China)	130	217
Yellow	668 (China)	1,600	479
Caroni	91 (Venezuela)	48	105
Amazon	5,776 (Several)	363	13
Orinoco	950 (Several)	87	18

† Adjusted according to sediment delivery ratios (Roehl, 1962).
Source: Holeman, 1968 (Modified). The shown sediment losses per unit area were calculated independently from data given in the first two columns. Yellow River data was derived from "Soil Erosion and Conservation in the Wuding River Valley" by Jiang Degi, Qi Laidi, and Tan Jeisheng, Yellow River Conservancy Commission, Beijing, China, April, 1980.

Table 3. Potential erosion for the Andean region, Peru.†

Soil loss range	Area	Percent of total
metric tons/km^2/year	km^2	
0–1,000	216,040	17
1,000–1,500	670,620	52
1,500–2,000	215,544	17
2,000–3,000	95,400	7.5
3,000–4,000	34,580	2.7
4,000–5,000	31,700	2.5
5,000–7,000	16,120	1.3

† By Fournier's Climatic Coefficient—Low, 1967.

Angola. In one of the few specific quantitative examples, Rapp (1977b) reported sediment yields for several defined catchments in Tanzania which would correspond to annual soil denudation rates of 3 to 14 metric tons/ha/year, with losses from one base plot amounting to 147 metric tons/ha/year. The countries in South and Central America within which severe erosion has been reported include Colombia, French Guiana, Peru, Mexico, Bolivia, Guatemala, Paraguay, Belize, Brazil, El Salvador, Venezuela, Honduras, Guyana, Nicaragua, Surinam, and Costa Rica. Among the regions most prone to erosion are the slopes of the Andes. Using Fournier's method for erosion hazard estimation, Low (1967) classified nearly 83% of the Andean Region of Peru as possessing potential erosion rates exceeding 1,000 metric tons/ha/year, and may thus be characterized as having severe erosion hazards (Table 3). Almost every island

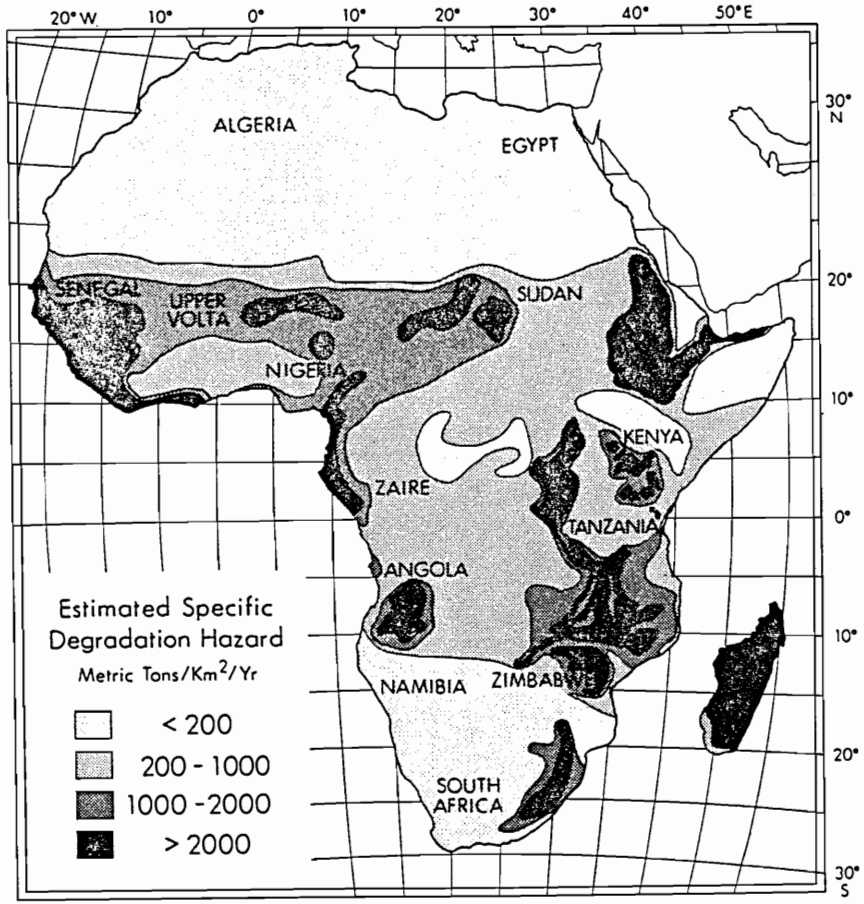

Fig. 4. Fournier's rainfall erosion hazard classes within Africa, South of the Sahara (modified).

in the Caribbean is subject to severe erosion (Ahmad, 1977). Thus, severe erosion incidence was reported in Haiti, St. Vincent, Dominican Republic, St. Lucia, Puerto Rico, Barbados, Trinidad, Dominica, Tobago, St. Kitts, Jamaica, and Antigua. Among these, Haiti is the western hemisphere's classical example where damage due to erosion appears to have reached the point of no return (Nepal being the Orient's counterpart). Aside from the previously shown river sediment load data (Table 2), there seems to be little documentation of actual severe erosion incidences in Asia and the Pacific. Countries and locations in that region for which serious problems have been indicated include Sri-Lanka, Philippines, China, India, Indonesia, Nepal (sub-tropic), Fiji, Malaysia, and Hawaii (state). Das (1977) estimated that 150 million ha in India are subject to many forms of erosion, 69 million ha of which are critically affected. Table 4 shows a breakdown of erosion extent in the Philippines indicating that in each of 14 provinces, more than 50% of the land area is affected

Table 4. Estimated erosion extent in the Philippines. †

Province	Area affected	Province	Area affected
	ha (%)		ha (%)
Batanga	256,059 (83)	Abra	248,102 (65)
Cebu	371,307 (76)	Iloilo	337,132 (64)
Ilocos Sur	198,225 (74)	Cavite	77,999 (61)
La Union	96,565 (70)	Rizal	121,790 (58)
Batanes	13,439 (68)	Capiz	243,079 (55)
Bohol	269,074 (66)	Marinduque	47,593 (55)
Masbate	269,516 (66)	Negros Occ	385,203 (50)
35 other provinces with 4.5 to 48%			
Total affected	8,895,948 30%		

† Miranda, 1978.

by erosion. Interestingly, several of the countries of Indo-China, including Thailand, are among the few where erosion can still be prevented from causing extensive irreversible damage by adequate and timely preventive measures.

The brief account provided above, and expanded elsewhere (El-Swaify et al., 1979) indicates that existing and potential rainfall erosion problems in the tropics are so extensive as to warrant serious concern on behalf of scientists and policymakers.

IMPACTS OF RAINFALL EROSION IN THE TROPICS

Documented literature, published or unpublished, on the impacts of rainfall erosion in the tropics is even more spotty than that on extent. In this paper, therefore, we will draw on experiences from different regions to illustrate three major impacts of erosional processes, namely on soil productivity to crops, flood hazards, and the life-expectancy of water-storage structures. Although the environmental impacts of delivered sediment (e.g., changes in water quality) represent a major concern in the USA (Agricultural Research Service, 1975), these are probably only secondary considerations in developing tropical countries.

Erosion and Soil Productivity

Changes in farm productivity as a result of soil loss are the major concern of agronomists dealing with erosion. Farms on both eroded (upland) and depositional (low-lying) sites are affected by erosion. Little information is available on the latter aspect, although it has often been argued that deposited sediments are beneficial to farm productivity. This is based on the fact that floodplains and deltas which have been formed over geologic times are often the location for very productive soils. The authors contend that, over a short span of one or a few rain seasons, delivered sediment may do more harm than good. The sediment may be so low in nutrient content and supplying capacity that even controlled delivery would be of little value to growing crops. Often, as observed by the authors in certain locations in northeast Thailand, uncontrollable de-

Table 5. Effect of topsoil depth on the yield of corn. †

Depth of topsoil	Indiana	Iowa	Missouri	Ohio
cm	kg/ha			
0	1,062	--	894	--
5	1,789	3,131	1,389	--
10	2,292	3,857	2,124	1,884
15	2,683	4,640	2,572	2,594
20	3,019	5,422	3,019	2,857
23	--	--	--	3,326
25	3,242	5,702	3,354	--
30	3,578	6,988	3,578	--
33	3,745	--	--	--

† Adapted from USDA, SCS-TP-75, 1949.
Source, Huat (1974) modified.

livered sediment is a detriment to production as it buries productive low-lying land thus destroying crops and preventing land cultivation by victimized small-scale farmers in the short term. Furthermore, when the origin of deposited sediment is impoverished subsoil from severely eroded uplands, farm productivity may be severely curtailed even in the long term.

Scattered information is available on the effects of soil loss on the productivity of eroded sites. When erosion is so severe and the soil is so shallow that complete denudation occurs, soil productivity is eliminated in that the soil itself is lost as a resource. Such cases have been reported in some heavily exploited hilly regions such as Haiti. In the more common cases of partial erosion, "top soil" removal has been generally associated with reductions in crop yield. Huat (1974) reviewed some of the literature on the effects of top soil depth on the yields of corn and other crops, mostly from the U.S. Midwest. As shown in Table 5, severe decline in corn yield occurs on all soils. However, the degree of decline and the yield maintained by the eroded soil highly depend on soil type and the extent of nutrient replenishment in and physical rehabilitation of the eroded soil. Because of the extreme site-specificity of this phenomenon, the above data cannot be quantitatively extrapolated to the widely diverse soils of the tropics. In two of the few examples of available data from the tropics, Huat (1974) and Siew and Fatt (1975) compared the effects of soil loss on the yield of maize in marginal and productive soils. As expected, their data (Fig. 5a, b) showed that growth as well as yield declines with soil removal were more severe in the first soil than in the second. Lal (1976) also showed general yield reductions due to soil removal for both maize (*Zea mays* L.) and cowpeas (*Vigna unguiculata* L.) on the Alfisols of Western Africa. He illustrated (Fig. 6) that yield declines for the first crop (~52% with 10 cm loss) were less dramatic than for the second (~38%). Both of the above studies, as for most previous studies, utilized surface scraping techniques to simulate soil erosion. This technique, while probably more drastic than natural erosion processes on continually tilled lands, is convenient because of the extremely long time necessary to obtain sufficient soil losses for affecting crop production under natural rainfall.

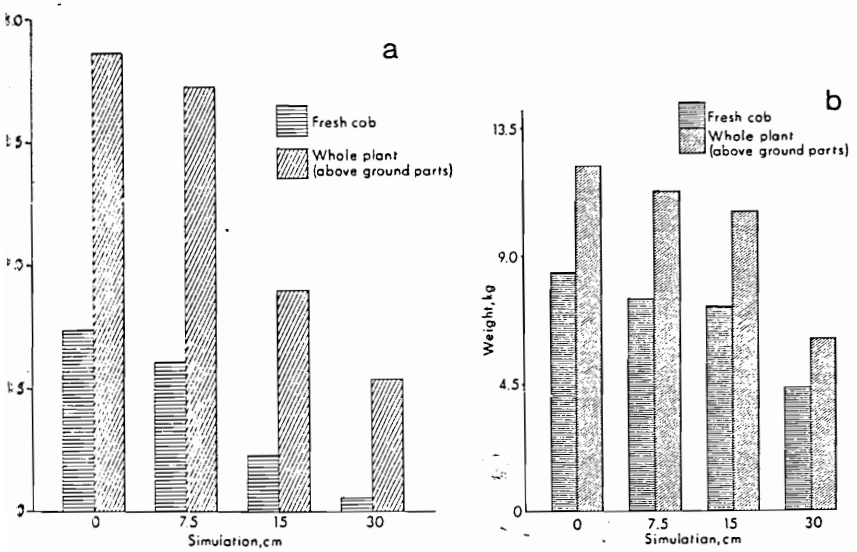

Fig. 5. Effects of simulated erosion on the yield of maize in Malaysia. a. for a cobbly soil b. for a deep soil.

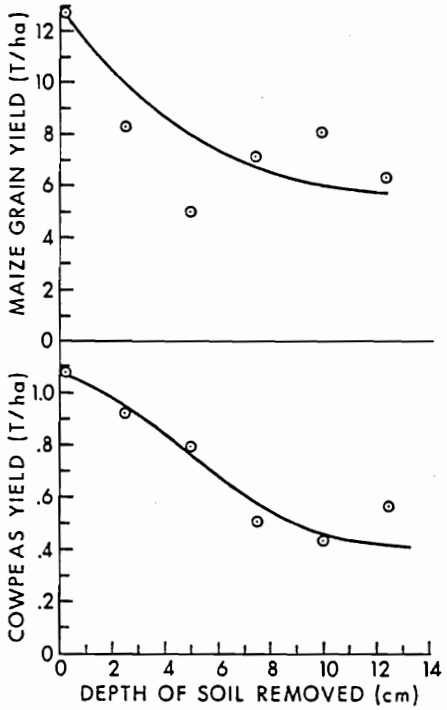

Fig. 6. Effects of soil removal on the yields of maize and cowpea on Alfisols.

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Yield declines as a result of erosion have been shown to be due to one or both of two factors. First is the loss of organic matter and soil nutrients associated with removed soil. It is safe to state that these losses are not strictly proportionate with depth in highly weathered (oxidic) tropical soils in which nutrients are most concentrated, near the surface. Table 6 shows some typical nutrient distributions with depth for eroded and non-eroded Ferralsols (Oxisols). Figure 7 is a composite of available data showing the projected extent of N and P losses associated with varying

Table 6. Selected nutrient distribution data for eroded and non-eroded Ferralsols. †

Profile	Depth cm	pH	C%	P ppm	Zn ppm	Cu ppm	Exchangeable cations meq/100 g Ca	Mg	K	H
D_1-eroded	0–15	4.51	1.40	6	1.0	5.7	1.37	0.9	0.15	12.1
	15–30	4.59	1.34	<2	0.9	4.1	2.08	1.16	0.11	11.3
	30–60	4.50	--	<2	1.1	3.5	1.50	0.70	0.10	11.8
	60–90	4.48	--	<2	1.0	3.3	1.21	0.48	0.09	11.9
D_2-Non-eroded	0–15	5.29	2.59	33	3.50	31.0	5.21	2.05	0.32	8.3
	15–30	4.78	1.22	5	0.9	4.4	2.28	1.79	0.18	8.4
	30–60	4.49	0.98	3	1.9	4.2	1.76	1.32	0.19	8.1
	60–90	4.29	0.53	3	5.5	8.2	1.20	0.58	0.14	6.6

† Moberg, 1972.

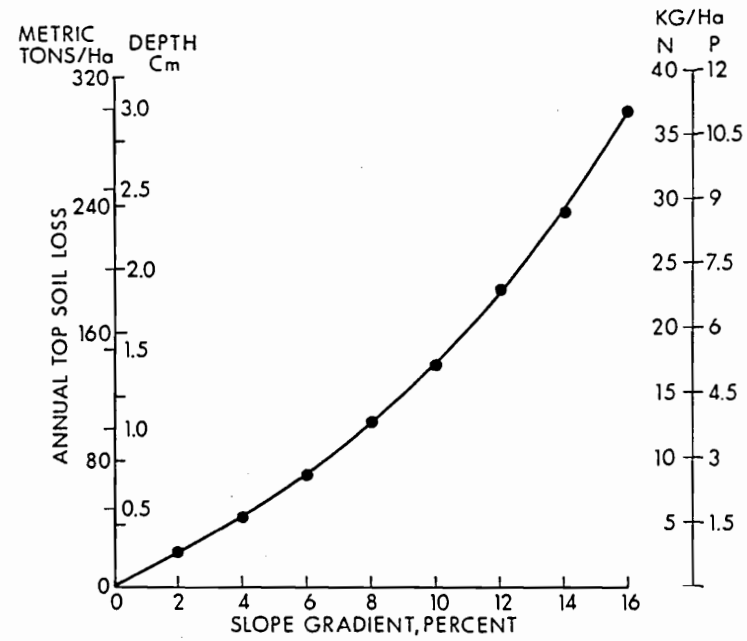

Fig. 7. Potential soil and nutrient losses from an unprotected tropical Oxisol (clayey, kaolinitic, isohyperthermic Tropeptic Eutrustox) in relation to steepness of slope. Calculations are based on experimentally measured soil erodibility, on standard slope length of 22 and 1,200 m annual rainfall with a corresponding erosion index of 350.

Table 7. Effect of removed soil depth on root development in cowpeas. †

Depth of soil removed	Root number	Average length	Max. depth	Lateral spread	Dry weight
cm		cm			g/plant
0	15	10.7	27	29	0.26
2.5	10	7.4	17	10	0.11
5.0	10	9.1	25	12	0.11
7.5	9	8.2	30	11	0.11
10.0	8	8.1	24	12	0.06
12.5	9	6.7	12	7	0.05

† Source, Lal, 1977.

Table 8. Effect of removed soil depth on root development in maize. †

Depth of soil removed	Root number	Average length	Max. depth	Lateral spread	Dry weight
cm		cm			g/plant
0	5.1	21.4	25	55	5.07
2.5	24	19.8	18	40	1.24
5.0	24	15.3	13	50	1.03
7.5	20	18.1	14	40	0.71
10.0	22	13.2	14	35	0.42
12.5	21	15.0	11	35	0.67

† Source, Lal, 1976.

degrees of erosion of an Oxisol from Hawaii. This aspect of erosion is a major consideration for the typical subsistence (tropical) farmer due to his lack of resources to replenish lost nutrients and thus sustain production at levels which correspond to those obtained by his U.S. or Western counterpart. To aggravate the problem, inadequate crop stands obtained on depleted soils contribute little to soil protection against further soil erosion and decline in organic matter and nutrient levels.

The second factor responsible for reduced productivity is physical degradation of soil within the root-zone. Often, the "subsoil" strata remaining after erosion are characterized by the presence of barriers to root proliferation (such as horizons of high bulk density or hard pans indurated by sesquioxides). Lal (1976) showed that root development of cowpeas (Table 7) and maize (Table 8) was increasingly restricted with more soil removal. This was explained by the poor water retention and transmission properties of exposed soils.

Hydrologic and Sedimentation Impacts

Floods caused by uncontrolled runoff are frequently natural phenomena associated with peak rainfall seasons. However, as stated earlier, the natural vegetation in high rainfall areas is generally adequate for minimizing runoff and erosional losses during those seasons. Increasing human activity in these areas, frequently dependent on deforestation, have been reported to disturb the natural hydrologic patterns so as to

Table 9. Siltation rates of selected reservoirs in India. †

Reservoir	Annual rate of siltation, 10^6 m³ Assumed	Observed
Bhakar (Punjab)	28.4	41.6
Panchet (DVC, Bihar)	2.5	11.8
Tungabhadra (Karnataka)	12.1	50.6
Nizam Sugar (Andhra Pradresh)	0.66	10.8
Ukai (Gujarat)	9.22	26.8

† Source, Patnaik, 1975.

produce floods previously unknown, to increase the destructiveness of existing floods, to induce water deficits at the location of disturbance due to excessive water losses by runoff and evaporation, and to accelerate soil losses by erosion (Eckholm, 1976 among others).

The specialized topic of flood hazards is adequately treated in many national and international publications and we do not intend to discuss it here in any detail. However, it is worthwhile to note that increased human disturbance of natural catchment areas is probably one major cause for the increasing frequency of disastrous floods in two major forms. First, it appears that water storage dams designed for river flood peaks which prevailed decades ago, collapse from the sustained increasing loads associated with recent floods. The estimated loss of perhaps more than 5,000 lives in the city of Morvi (480 km northwest of Bombay) during August 1979 is only one recent example of this problem. Second, periodic floods which destroy life and property are now common place in many countries during the rainy season. Frequently referred to as "natural disasters," devastating floods hit the Indian subcontinent with regularity. In 1977, the latest year for official statistics, nearly 10,000 persons perished as a result of floods in India. In the 1979 summer rainy season, crop damage alone in the northeastern state of Bihar was estimated at $375 million (Marshall, 1979).

Associated with increased runoff volumes from forests after disturbance are also large increases in soil loss. McElroy et al. (1976) estimated that exploiting forestland for planting row crops, mining, and construction increased the magnitude of surface erosion by 100 to 1,000-, 1,000-, and 2,000-fold, respectively. Two major agricultural consequences of this are the burial of low-lying crop lands, as discussed earlier, and the reduced life-expectancy of water storage structures. Among the dams for which siltation data are available, the Aswan High Dam (Egypt), the Matumbulu dam (Tanzania), the Kisongo dam (Tanzania), the Ambuklao dam (Philippines), and the Mangla dam (Pakistan) are estimated to receive 139,000,000, 19,800, 3,400 to 5,800, and 3,700,000 metric tons/year of sediment, respectively. The useful life of the Kisongo dam for water storage ended after only 15 years (in 1975) and by now is almost fully silted. The life expectancy for the remaining dams is estimated at 100, 30, 32, and 75 years from construction, respectively. Table 9 shows an example of a typical situation, this case in India, whereby actual siltation rates of reservoirs always exceeded those which were ex-

pected at the time of construction planning. It is not possible to determine whether the discrepancy is due to the planners' optimism or to the increased siltation rates due to population disturbances within river catchments in recent years.

The above are only a few of the examples which clearly demonstrate that rainfall erosion in the tropics has impacts which, though only sparsely documented, should be of grave concern to agronomists, conservationists, and policymakers.

QUANTITATIVE CAUSATIVE PARAMETERS

In general, the conditions enhancing erosion by water at a given site are a rainfall of high intensity and long duration; high rates of overland flow from adjacent uplands; soils with poor structure; low infiltration rates; or lack of coherence between top- and subsurface-layers, long and steep slopes, sparse or absent vegetation and/or organic residue, and land cultivation and tillage operations which are directed along the existing slope. In the tropics, as expected, these are the very conditions which favor high rates of soil erosion. However, the contribution of each of these conditions to the overall erosion process is different in the tropics from other regions. The Universal Soil Loss Equation (USLE) of Wischmeier and Smith (1978) quantifies all contributing parameters for inter-rill and rill erosion as follows:

$$A = R \times K \times L \times S \times C \times P$$

in which A is the total soil loss, R the rainfall (erosivity) factor, K the soil (erodibility) factor, L and S slope length and steepness factors, C the crop cover factor, and P the land management (supporting practices) factor. Quantitative values for each factor in the equation have been developed by Wischmeier and Smith (1978) and were generally helpful for predicting erosion extent and prescribing required control measures in many states within the USA. The utility of this equation for use in the tropics will be the subject of another paper (Foster et al., 1981) in this publication. It is instructive for our purpose to state that the USLE is universal in the sense that it identifies all the parameters which control soil loss by water (Wischmeier, 1976). However, quantitative use of the equation requires site specific values of component parameters. On the one hand, little has been done to obtain such values and thus "extend" the use of this equation to tropical regions. On the other hand, no alternative comprehensive models have been developed for use in these regions. The Soil Loss Estimation Model for Southern Africa (SLEMSA) proposed by Elwell (1977) represents one modification of the USLE for simplified application in developing countries. However, this model too lacks the verification necessary for wider use. In the next paragraphs we will present available information on erosion causative parameters with particular reference to potential use in the USLE or similar models.

Rainfall Erosivity in the Tropics

Annual totals and monthly rainfall distribution patterns for selected locations throughout the tropics are shown in Fig. 8 and 9. Although some locations receive more or less equal quantities of monthly rainfall, most patterns indicate that rainfall hazard is variable throughout the year. Total rainfall also varies greatly reaching as high as 5,179 mm at the Akyab station (Burma) and as low as 28 mm in Cairo (Egypt). Neither the total annual rainfall nor the monthly distributions alone suffice for quantifying rainfall erosivity. For this purpose indices based on kinetic energy, momentum, intensity, or their combinations were successful. This indicates that individual storm characteristics, particularly intensity and duration (both of which are determined by raindrop characteristics, i.e., number, size, and terminal velocity) together with the frequency of occurrence are the most important criteria. Unfortunately, such data are scarce for tropical storms. Jackson (1977) provided an up-to-date account of tropical rainfall characteristics. Table 10a shows selected rainfall intensity data for several locations, with one location in the continental USA for comparative purposes. The table shows that storm intensities, particularly for short durations, can reach much higher values for tropical than for temperate areas. When intensity and energy data are combined into Wischmeier's erosivity (EI_{30}) index (Wischmeier and Smith, 1978), the high erosivity of tropical rainfall is confirmed. Table 10b shows sample data collected by the authors from various published and unpublished sources (El-Swaify et al., 1979) together with the highest value reported for the continental USA (Wischmeier and Smith, 1978). Regardless of whether or not the EI_{30} is a perfectly valid erosivity index in the tropics (there are undocumented speculations that it may overestimate rainfall erosivity), the relative trends in the table should hold true. These indicate the much higher erosivity of tropical rainfall. It is emphasized, however, that the success of EI_{30} as an erosivity index in temperate regions needs to be verified for the tropics. Similarly, alternative indices proposed by other authors (Hudson, 1973 and Lal, 1976) have not been tested outside their original locations.

Erodibility of Tropical Soils

Erodibility is the quantitative index of inherent soil susceptibility to erosion by water. In the USLE it is intended to represent the mean annual value of soil loss in metric tons /2.24/ha/EI_{30} units (tons/acre/EI_{30}) from a 22.2 m long plot situated on a uniform of 9% slope, under continuous fallow and tilled parallel to the slope. The constant 2.24 is the conversion factor between English and Metric units. Experimentally measured erodibility values for all soils vary widely from 0 to 0.69 with those for tropical soils also widely variable at 0 to 0.55 (El-Swaify and Dangler, 1977). Table 11 gives a summary of soil erodibility values for different soils as available from published and unpublished sources. Because all 10 orders of *Soil Taxonomy* are present in the tropics, data from outside the tropics are in-

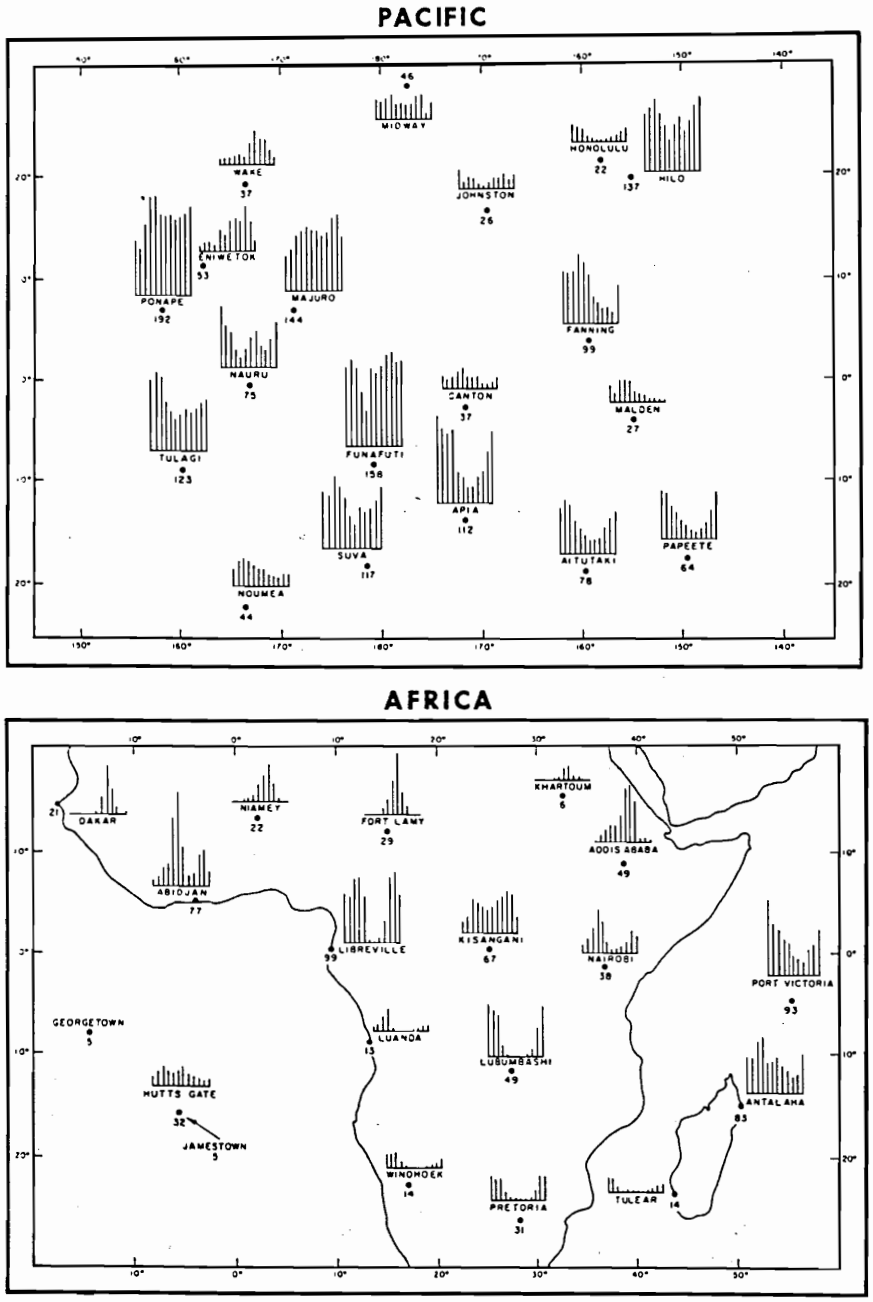

Fig. 8. Mean monthly rainfall for Pacific and African stations in the tropics (After Atkinson, 1971).

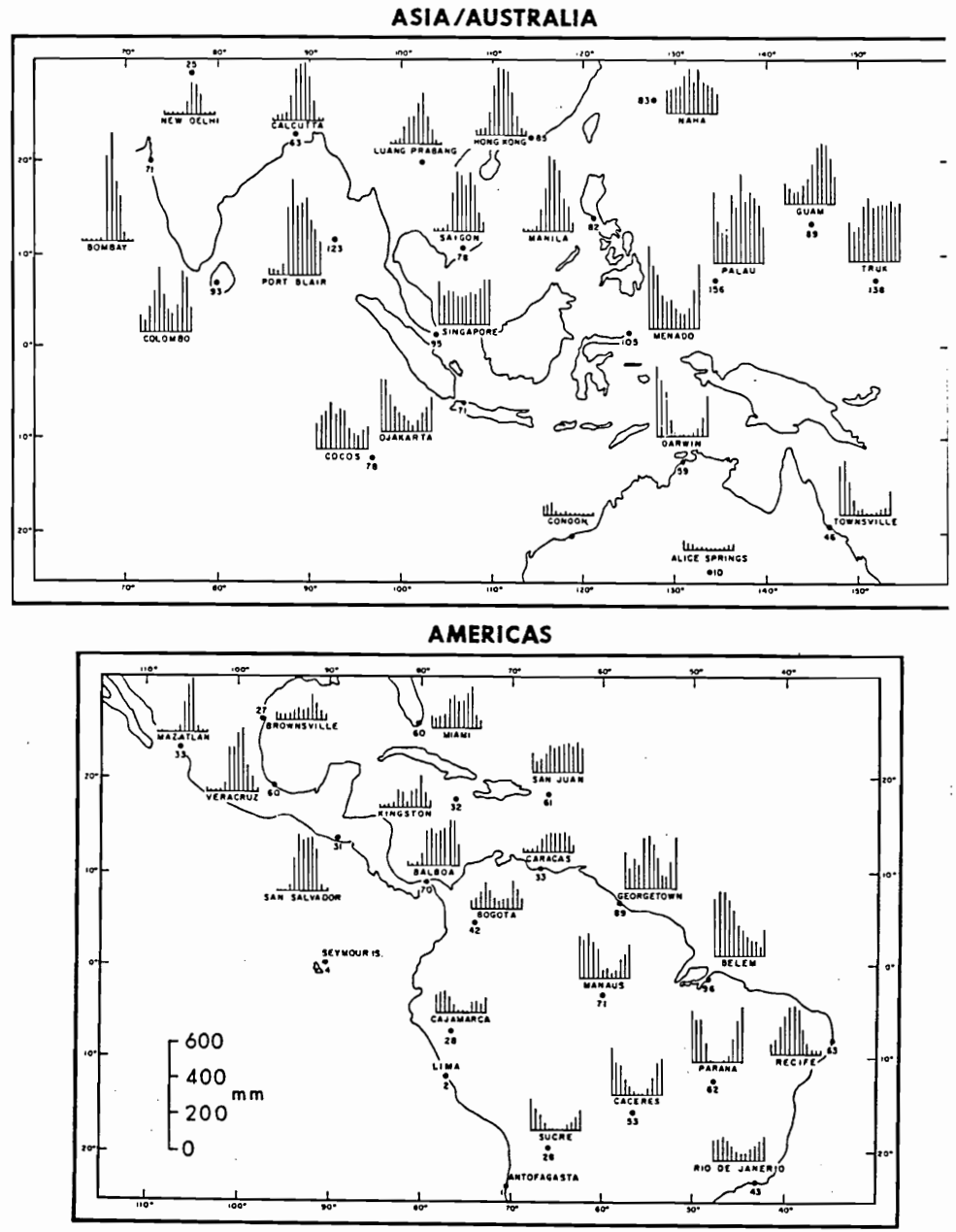

Fig. 9. Mean monthly rainfall for Asian/Australian and American stations (After Atkinson, 1971).

Table 10a. Selected data for high rainfall intensity rates in the tropics.†

Location	I	Duration	Date
	mm/hour		
Plumb Point, Jamaica	792	15 min	5-12-62
Monrovia, Liberia	478	15 min	8-01-74
Miami, Florida	192	15 min	--
Colombo, Sri Lanka	170	90 min	--1907
Ibadan, Nigeria	162	15 min	6-16-72
Waialua, Hawaii	142	15 min	4-18-74
Belvouve, La Reunion	121	9 hours	2-(28-29)-64
Belvouve, La Reunion	112	12 hours	2-(28-29)-64
Belvouve, La Reunion	91	18.5 hours	2-(28-29)-64
Cilaos, La Reunion	78	24 hours‡	3-(15-16)-52
Cilaos, La Reunion	52	2 days	3-(15-17)-52
Baguio, Philippines	49	24 hours	7-14-11

† Modified from Jackson, 1977, Lal, 1977 and Unpublished sources.
‡ This storm produced the highest 24-hour rainfall on record (1,869.9 mm or 73.6").

Table 10b. Selected data for rainfall erosivity according to the EI_{30} index.

Location	Index
S. Louisiana	600
Mangalore (W. India)	1457
Conakry (Guinea)	2000
Douala (Cameroon)	2000
Laupahoehoe (Hawaii)	740
Hilo (Hawaii)	780
Campinas (Sao Paulo)	690
Jakarta	2307

cluded as well. It is noted that variations between the different orders and even within the same order are so wide that no single image can be drawn for a "stereotype" tropical soil. Indeed, the wide diversity of tropical soils is such that a narrower basis of classification (perhaps at the family level) is required to rank the erodibility of soils from different regions. Unfortunately very few workers have provided such information, as exemplified by Table 11f. One trend that emerges from Table 11 is the tendency of the more weathered soils (Oxisols and Ultisols) to be generally less erodible and the less weathered soils (Alfisols, Aridisols, Mollisols, and Vertisols) more erodible. This has been attributed to good water transmission properties and coherent structure in the first groups (El-Swaify, 1977) and the lack of both in the others. The lower erodibility values shown for the tropical areas in Table 11a and b may reflect some of the hydrologic and structural attributes of Oxisols. However, they may also be artifacts of the variations in experimental techniques and computation methods of different workers. If indeed the erosivity of tropical rainfall is grossly overestimated, then the K values derived from experiments under natural rainfall are expected to be low.

Experimental measurements of soil erodibility are expensive and time consuming. Therefore, and because the inherent susceptibility of soil to erosion is determined by basic physical, chemical, and mineralogical

Table 11. Erodibilities of soils within different taxonomic orders.

a. Alfisols and Aridisols

Series or I.D.‡	Location	K-value
Dunkirk, SL	Geneva, N.Y.	0.69
Dayton,	Oregon	0.54
St. Clair†	Michigan	0.48
Keene, SL	Zanesville	0.48
McGary†	Indiana	0.36
Kawaihae, SL	Hawaii	0.35
Rabat	Morocco	0.35
Hagerstown, SLC	Pennsylvania	0.31
Putat	Indonesia	0.26
Gampela	Upper Volta	0.25
Saria	Upper Volta	0.25
Seta	Senegal	0.25
Punung	Indonesia	0.14

b. Mollisols and Vertisols

Series or I.D.‡	Location	K-value
Mayberry†	Nebraska	0.67
Pawnee†	Nebraska	0.45
Shelby, L	Missouri	0.41
Marshall, SL	Iowa.	0.33
Lualualei	Hawaii	0.29
Austin, C	Texas	0.30
Jegu	Java	0.20
Portageville	Missouri	0.05

c. Inceptisols

Series or I.D.‡	Location	K-value
Pakini, SL	Hawaii	0.55
Naalehu, SLC	Hawaii	0.21
Waipahu, SC	Hawaii	0.19
Kukaiau, SCL	Hawaii	0.17
Pandura, L	Hawaii	0.11
Hilo, SLC	Hawaii	0.07
Darmaga	Indonesia	0.04
Juncos, C	Puerto Rico	0.02

d. Ultisols

Series or I.D.‡	Location	K-value
Cecil, SCL	Georgia	0.36
Tea (Un-named)	Sri Lanka	0.31
Cecil, SL	Georgia	0.23
Waikane, SC	Hawaii	0.09
Freehold, LS	New Jersey	0.08
Humatas, C	Puerto Rico	0.00

e. Oxisols

Series or I.D.‡	Location	K-value
Molokai, SCL	Hawaii	0.22
Wahiawa, SC	Hawaii	0.14
Bouoke	Ivory Coast	0.12
Apiopodoume	Ivory Coast	0.10
Agonkaney	Benin	0.10
Korhoga	Ivory Coast	0.02
Catalina-Cialitos, C	Puerto Rico	0.01

f. Miscellaneous soils

I.D.‡	Classification	Location	K-value
Marl	Clay Mix	Morocco	0.6
Marl	Loose	Morocco	0.5
Marl	Cemented	Morocco	0.4
Marl	Sandy	Morocco	0.3
Schist	Acid	Morocco	0.2
Sentolo	Lithosol	Indonesia	0.14
Citaman	Latosol	Indonesia	0.10
Sands	Pepply	Morocco	0.10
Limestone	Sandstone Mix	Morocco	0.05
Darmaga	Latosol	Indonesia	0.03

† Subsoil.
‡ Identification.

properties, some workers have proposed the use of easily measured properties to predict erodibility values. Wischmeier et al. (1971) and Roth et al. (1974) proposed predictive nomographs for light and heavy textured soils and subsoils, respectively. The first has found very wide use, even in the tropics. As discussed in detail elsewhere (El-Swaify, 1977, El-Swaify and Dangler, 1977, and El-Swaify et al., 1979) the ranges of parameter values encountered in soils investigated by both groups of authors differ so greatly from those found in tropical soils that neither nomograph is valid

in these soils. There is indeed an urgent need to develop valid techniques for predicting the erodibility of the widely diverse soils of the tropics.

Topographic Factors

Slope gradient and length have long been known to have profound effects on runoff and erosion. However, the quantitative contributions of these two variables to runoff and soil loss have been the subject of many controversies (e.g., Lal, 1977). Wischmeier and Smith (1978) elected to calculate the slope length (L) and slope gradient (S) factors for the USLE using the models $E = b\lambda^{0.5}$ and $E = a + cs + ds^2$, respectively. In these equations E refers to the soil loss per unit area, λ the slope length, s the slope gradient, and a, b, c, and d to empirical constants. The formulated LS charts based on these factors still represent the most widely used means of quantifying topographic effects. With the exception of Hudson's (1971) slope gradient equation $E = ds^2$ (the terms have the same meaning as above), no similar relationships have been developed in the tropics. Because the relative effects of S and L on runoff and erosion are probably site-specific and their contributions to soil removal by rainfall splash and overland flow soil specific, such data are urgently needed for the tropics. In addition, the validity limits on S and L upon which Wischmeier and Smith's charts (1978) were based (2 to 18% and 7 to 100 m, respectively) are inadequate for many lands upon which cultivation is commonplace in the hilly regions of the tropics.

It is important that topographic effects on soil loss be quantitatively established for tropical regions as erosion control practices which are based on land-shaping cannot be successfully designed without such information.

Crop and Land Management Factors

The protective characteristics of many crops against rainfall erosion have been subject to extensive studies in temperate regions. In the USA, planting and harvesting time, cover characteristics during different growth stages, rotations, and residue management have been incorporated together with seasonal distribution of rainfall erosivity to formulate the C factor of the USLE. No similar information is available for tropical crops, although significant effects on soil loss have been well established for some locations due to crop and residue characteristics (e.g., Lal, 1977). It is worth noting here that certain popular tropical crops such as cassava (*Manihot esculenta* Crantz) and oil palm (*Elaeis guineensis* Jacq.) appear to provide little protection to the soil as currently managed. This is particularly compounded on steep slopes and because protective crop residue is difficult to maintain due to the rapid decomposition encountered under tropical environments. Emphasizing soil protection by utilizing effective management alternatives (including intercropping with fast growing ground cover; effective use of residue and timing of planting and harvesting operations) is urgently needed.

Similar lack of information exists on the role of supporting land management practices in determining the magnitude of soil loss by erosion in the tropics. In the USA that role has been quantified as the P factor in the USLE (Wischmeier and Smith, 1978). Tillage against the slope (contouring), contour strip-cropping, terracing, and combinations thereof can be successful in reducing, diverting, or slowing down runoff flowing from sloping lands. The above authors formulated quantitative values for the extent to which the soil loss from lands of different slopes may be reduced from the maximum value (P = 1) by alternative tillage practices and for slope-length limits associated with each. The formulations are often used in tropical countries but have not been actually tested to determine quantitative applicability. Lal (1977) has advocated minimum or no tillage as the foremost practice for reducing soil loss ($P \rightarrow 0$) from cultivated Alfisols in western Africa.

Socioeconomic Considerations

Understanding the causative parameters of the erosion process as discussed above will provide conservationists with the technical tools to estimate soil losses under a particular set of conditions and to reduce these losses by imposing necessary modifications or management parameters (primarily L, C, and P). The availability of these tools alone, however, will not assure implementation or successful soil conservation. Economic considrations (including effective incentives to the farmer), regulatory and policymaking provisions, land tenure systems, watch-dog agencies, immediate pressures due to continually increasing population densities and associated use of marginal lands for cultivation, size of landholdings, prevailing patterns of farming systems, prevailing political trends, cultural and religious taboos, among other factors, can be limiting to the implementation of available technology. It seems that population density is an appropriate barometer of these socioeconomic factors. It is in those regions with high population density where expanded exploitation, including farming, of marginal hilly lands is a hazardous necessity. Ironically, it is also in those very regions where greatest need exists to protect the rapidly diminishing or degrading soil resources. This vicious cycle which is dictated by increasing human needs for food, fiber, and energy cannot be overlooked in a realistic planning of land utilization and conservation.

CONCLUSIONS

Available evidence for the serious magnitude of rainfall erosion in the tropics is spotty but convincing. Although the different impacts of accelerated erosion (e.g., on soil productivity) have only been rarely documented, it is evident that these are generally detrimental to developing tropical countries as a whole and to subsistence farmers in particular. The common lack of quantitative understanding of causative parameters is a serious bottleneck in the way of conservation-effective land-use planning

and utilization in the tropics. More effort is needed to develop such understanding and thus the required selectivity in transferring or adopting existing technology to the tropics. Such adaptation is strongly dependent on socio-economic considerations which are largely based on population-density pressures and requirements. The following chapters will elaborate further on many of the aspects discussed here.

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