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Soil Erosion by Water in the Tropics

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ABBREVIATIONS

AID	Agency for International Development (United States)
ARS	Agricultural Research Service (USDA)
ASA	American Society of Agronomy
ASAE	American Society of Agricultural Engineers
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CSWCRTI	Central Soil and Water Conservation Research and Training Institute (Dehra Dun, India)
CTAHR	College of Tropical Agriculture and Human Resources (UH)
EEC	European Economic Community
FAO	Food and Agriculture Organization (UN)
HESL	Hawaiian Environmental Simulation Laboratory (UH)
IAHS-AISH	International Association of Hydrologic Science—Association International de Science Hydrologique
ICAR	Indian Council of Agricultural Research (Dehra Dun)
ICRISAT	International Crops Research Institute for the Semiarid Tropics (Dehra Dun)
ICSC	International Conference on Soil Conservation (Silsoe, U.K.)
IITA	International Institute of Tropical Agriculture (Nigeria)
IRRI	International Rice Research Institute
JCRR-MARDB	Joint Commission on Rural Reconstruction and Mountain Agricultural Resources Development Bureau (Taiwan)
LDC	Less developed country
NAS	National Academy of Sciences
NIFTAL	Nitrogen Fixation by Tropical Agricultural Legumes project (UH)
OAS	Organization of American States
ORSTOM	Office de la Recherche Scientifique et Technique Outre-Mer
PCARR	Philippines Council for Agricultural and Rural Research
RRIM	Rubber Research Institute of Malaysia
SCS	Soil Conservation Service (USDA)
SCSA	Soil Conservation Society of America
TCNSPC	Technical Committee on Nonpoint Source Pollution Control
UH	University of Hawaii
UK	United Kingdom
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WMO	World Meteorological Organization

SYNOPSIS AND RECOMMENDATIONS

Existing knowledge allows erosion and conservation workers in the tropics to make some qualitative assessments of the extent and forms of rainfall erosion, approximate estimates of various causative parameters, crude evaluations of the various effects, and selected prescriptions of appropriate control measures. However, quantitative data on all these factors are spotty at best.

Determinations of the magnitude of existing and potential erosion have been conducted by widely different methods. Nevertheless, in several countries available evidence of the seriousness of the problem is convincing. Fortunately, evidence also indicates that degradation by erosion has yet to reach a critical stage in many countries.

Quantitative documentation of the impact of erosion, particularly its effect on soil productivity, has also been sketchy. Judgment of the severity of erosion has remained subjective and mostly dependent on how visible the problem is. Nevertheless, it is evident that erosion by water detrimentally affects the productivity of soils, both at the source and at the destination of sediments. Where it is most severe, erosion may result in the total loss of soil as a resource as well as of valuable associated vegetation. Other detrimental effects include deterioration of the quality and fish-producing capacity of destination water bodies, shortened life expectancy of reservoirs and water storage structures, and loss of valuable water through destructive floods from uncontrolled runoff.

There exists a general qualitative understanding of the roles of individual causative parameters in the tropical environment. However, the quantitative data necessary for predicting potential erosion and detecting critical management alternatives are rare. While the state of current knowledge allows approximate estimation of required improvements in land use for the elimination or reduction of loss of valuable soil, absence of necessary base-line data curtails the development of conservation practices applicable in the tropics. This lack of data also prevents objective evaluation of the applicability of conservation experiences (and models) developed outside the tropics. It is of serious concern that certain of these models are used indiscriminately without the scientific evidence required to test their applicability. The same data restrictions are responsible for the lack of an adequate basis on which to modify these models and make them applicable.

Conversely, the availability of vital data, and a system of dissemination, can increase the awareness of leaders and policymakers of the importance of the problem and the scarcity of trained specialists and practitioners in research and advisory services.

These assertions are supported by detailed accounts within this report and form the bases for the following recommendations:

1. A mechanism should be established whereby the concerted and coordinated efforts needed to meet identified priority needs may be exerted. We propose the organization of a collaborative network whose members would include concerned institutions in developing tropical countries together with selected international and U.S. institutions. The suggested name for the network is the Collaborative Network for Soil Erosion and Conservation in the Tropics (CONSECT).
2. While priority needs are not uniform for all developing tropical countries, major gaps emerge in several categories of frequent importance. It is proposed that CONSECT be utilized as the clearing house for information and for assisting member countries with cooperative program planning and implementation. Important program elements are to:
   a. provide information to leaders and policymakers concerning accelerated erosion and its serious impact. This service would be

provided to countries in which erosion has not yet reached severe proportions as well as those that already suffer severe problems.

b. Identify major research needs for the quantitative assessment of erosion sources, the extent of erosion, soil loss tolerances, and causative parameters. Joint evaluations need to be made of alternative research methodologies and of the transferability of certain aspects of available technology for erosion prediction and control in the developing tropics.

c. Enhance the development of effective extension and advisory services and information delivery systems in the areas of erosion and conservation.

d. provide appropriate means for meeting the training needs of member countries.

CHAPTER 1
INTRODUCTION

Civilizations have flourished or declined with abundance or shortage of their natural resources. Lowdermilk (1953) and Carter and Dale (1974) provided clear historical documentations in support of this observation. Soil and water, aside from people themselves, are the most important of these resources. The degradation of agricultural lands is a consequence of many and extremely diverse forces (FAO 1971, 1977*c*). A world with a human population of nearly 4 billion (United Nations 1977), increasing 2 percent per year, can hardly afford the harmful impacts of land degradation in any form. Beginning with the classic work of Jacks and Whyte (1939), such concerns have been expressed repeatedly, often with ample analytical documentation (FAO 1971, 1977*c*; Constantinesco 1976; Pimentel et al. 1976) and just as often with mind-boggling syntheses of previously reported observations (Eckholm 1976; Brown 1978). Even in the United States, where persistent and often successful soil conservation efforts have been made since the mid-1930s, there is still serious concern that much more needs to be done (Carter 1977).

Although soil erosion is often associated with deterioration or loss of water resources and may well be the most serious and least reversible form of land degradation in tropical environments, there is little or no documentation of the extent, impact, or causes of erosion in these regions. Yet the need for such documentation is acute because it is precisely in these regions that most of the human population of the world resides, faces constant critical shortages of food and energy, and has the fastest rate of expansion. Consequently, in tropical countries, there is ever-increasing pressure to cultivate forest lands that currently serve as vital watersheds and provide an important measure of environmental stability.

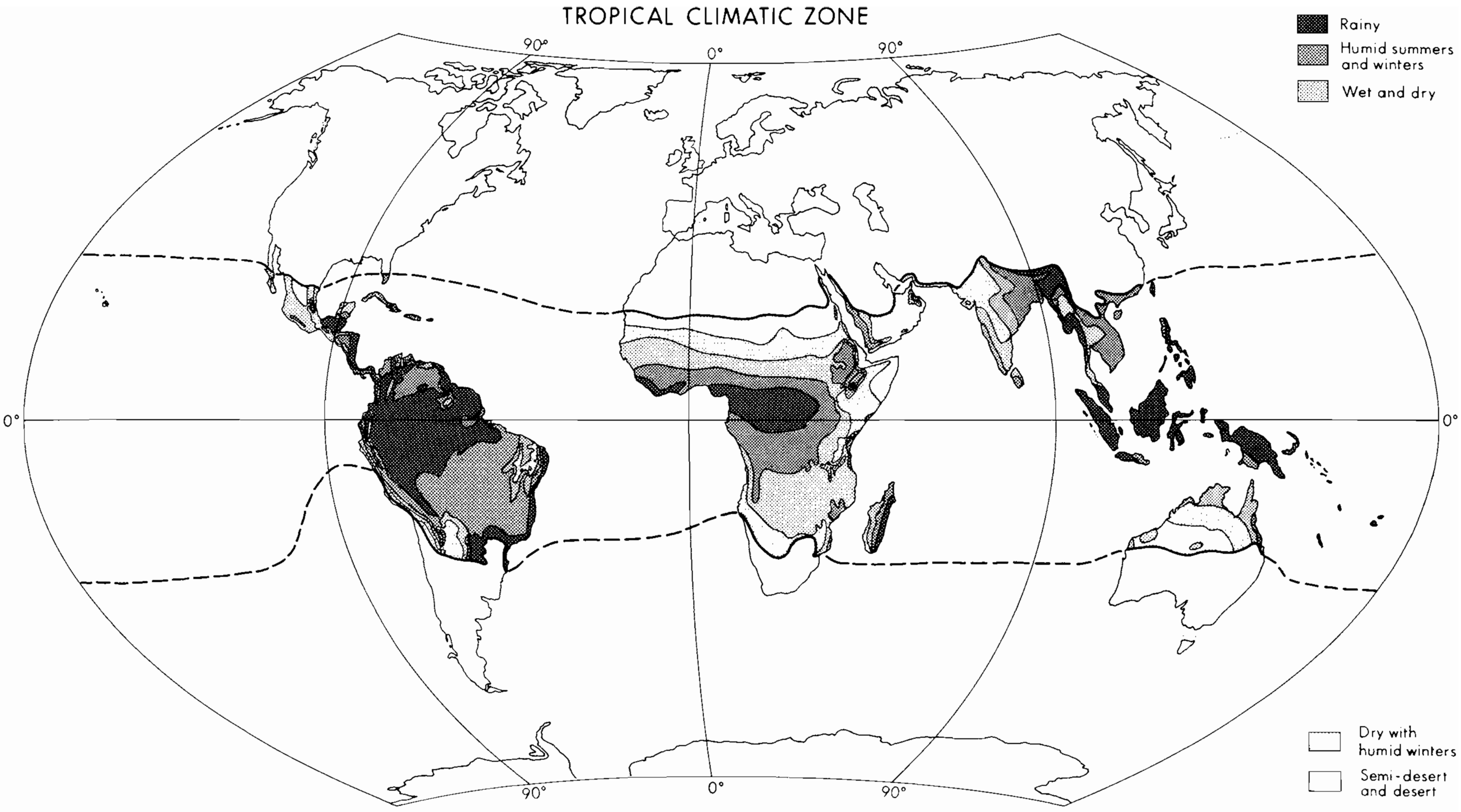
In this report, we attempt to provide a synthesized documentation of erosion problems in the tropics, based on available published literature, unpublished literature, correspondence, and site visits to selected countries. Although erosion by wind is recognized as a major hazard in the arid and semiarid tropics, the scope of this report is limited to erosion by water. We shall treat the tropical zone with the climatic subzones shown in Map 1; however, we shall make numerous references to concepts or data developed in the temperate regions because most of the available data on erosion research have been collected there.

FORMS OF WATER EROSION

The expression ''erosion by water'' has been used to describe many widely different phenomena, including the depletion of soil constituents by dissolution and leaching. However, in this book erosion will be defined as the ''wearing away of the land surface by running water, wind, ice, or other geological agents, including such processes as gravitational creep'' (SCSA 1976). For our purposes, it is particularly useful to distinguish two classes of erosion—geological and accelerated—although other classifications have been proposed and may be useful in particular situations (Arnoldus 1974).

Geological (sometimes called natural or normal) erosion is the inexorable and continuous process of evolution of the Earth's surface by such geological agents as rainfall, overland flow, snow melt, streams, and so on. As its name indicates, accelerated erosion is usually a more rapid process that is largely induced by such human practices as forest clearing, raising crops and domesticated animals, mining, and construction. It is this form of erosion by water, which is more detrimental but also amenable to limitation and control, that is the focus of this report.

Early in the study of erosion, the mode of running water on the land surface was considered to take es-



Map 1. Tropical climates of the earth. (Modified from Troll 1966)

sentially three forms: sheet, rill, and gully erosion (Bennett 1939). Sheet erosion, now frequently called interrill erosion, involves the more-or-less even removal of layers of soil from an entire segment of sloping land, and is by far the least conspicuous. Rill erosion results from the concentration in surface depressions of water that subsequently flows down slope along paths of least resistance thus forming microchannels or rills. Gully erosion is also channel erosion that has progressed so deeply and extensively that the land cannot be used for normal cultivation. While this view of erosion emphasized the role of overland flow, it was also realized that the energy associated with raindrop impact is an important factor (Cook 1936). Classic studies of raindrop splash indicated that the raindrop was the initiator of the erosion process (Ellison 1947*a, b*). Ellison provided a sequential separation of the erosion process into two parts—detachment and transportation of soil materials. He indicated that detachment of soil particles may be caused by either raindrop splash or surface (overland, sheet) flow (Ellison and Ellison 1947; Horton 1945). Transportation of soil particles generally occurs with overland flow but may also be accomplished by raindrop splash (Ellison 1944). Despite disagreement among erosion workers on the terminology associated with water erosion (Hudson 1971), all the foregoing terms are still in general use. A recent refinement in terminology has been the use of the term "interrill (prerill) erosion" to describe erosion caused by the overland flow of runoff as it moves at shallow depth for short distances until it concentrates in tillage marks, depressions, or previously eroded grooves (Meyer et al. 1975).

Aside from the general terms defined above, others have been used to describe a number of specialized types of erosion. These include piping, pedestal erosion, vertical erosion, and others. Piping (tunnelling, subsurface gullying, or percoline drainage) refers to a subsurface form of gully erosion encountered in soil profiles characterized by certain properties (Baillie 1975; Stocking 1976). These properties include a permeable upper horizon and an impermeable layer lower in the profile, a disturbed or cracked, sparsely vegetated surface, and a hydraulic gradient which favors soil removal from weak (dispersible, sodic) soil planes that are surrounded by stable soil (Crouch 1976, 1978). Unless modified by man, such a tunnel will ultimately form a gully. Pedestal erosion occurs when impermeable objects such as rocks, stones, or roots provide cover for a small part of the soil, leaving it protected in the shape of unique columns or walls, while the surrounding soil is eroded away. Pinnacle erosion is a similar form that results in the formation of towers or pinnacles of resistant soil. Hudson (1971) also recognized puddle erosion—the loss of soil structure by rain action; and vertical erosion—the translocation of fine particles from the surface to the subsurface soil. Figure 1 illustrates several forms of water erosion.

As will be noted and documented in this report, all the forms of erosion described above have been observed in the tropics. Although policymakers are generally more impressed by the spectacular forms and stark realities of gully and tunnel erosion, it is the less visible forms such as sheet, rill, and interrill erosion that cause the greatest cumulative damage—particularly to the agricultural potential of the land. The latter are widespread in area and occur continuously. Fortunately they are also the most predictable (quantitatively) and the most amenable to preventive and control measures (see chap. 5).

TOLERANCE LIMITS OR PERMISSIBLE SOIL LOSS

As a matter of principle, it would be desirable to avoid "permitting" soil to be eroded away under any circumstances. In reality, however, a certain degree of soil loss must be accepted as normal, for example, by the natural forces of geological erosion in undisturbed lands (Smith and Stamey 1965). In setting tolerable limits for soil loss, several factors have traditionally been considered. These include the anticipated rate at which soil renewal may occur, by *in situ* formation or imported deposits as a result of prevailing weathering processes; the effect of soil removal on soil productivity; and the impact of delivered sediments on the environmental quality of waterways or other destination points (Mannering 1981). As might be expected, tolerance limits for these three criteria do not necessarily have the same values.

There is no agreement in the literature on the length of time necessary to form a unit depth (1 cm) of soil. Boul et al. (1973) cited several authors in giving estimates ranging from 1.3 to 750 yr/cm. This wide variation is attributed to the different conditions (such as climatic regimes and parent materials or rocks) and criteria (such as total soil depth or soil profile development through horizon differentiation) employed by different authors to measure the

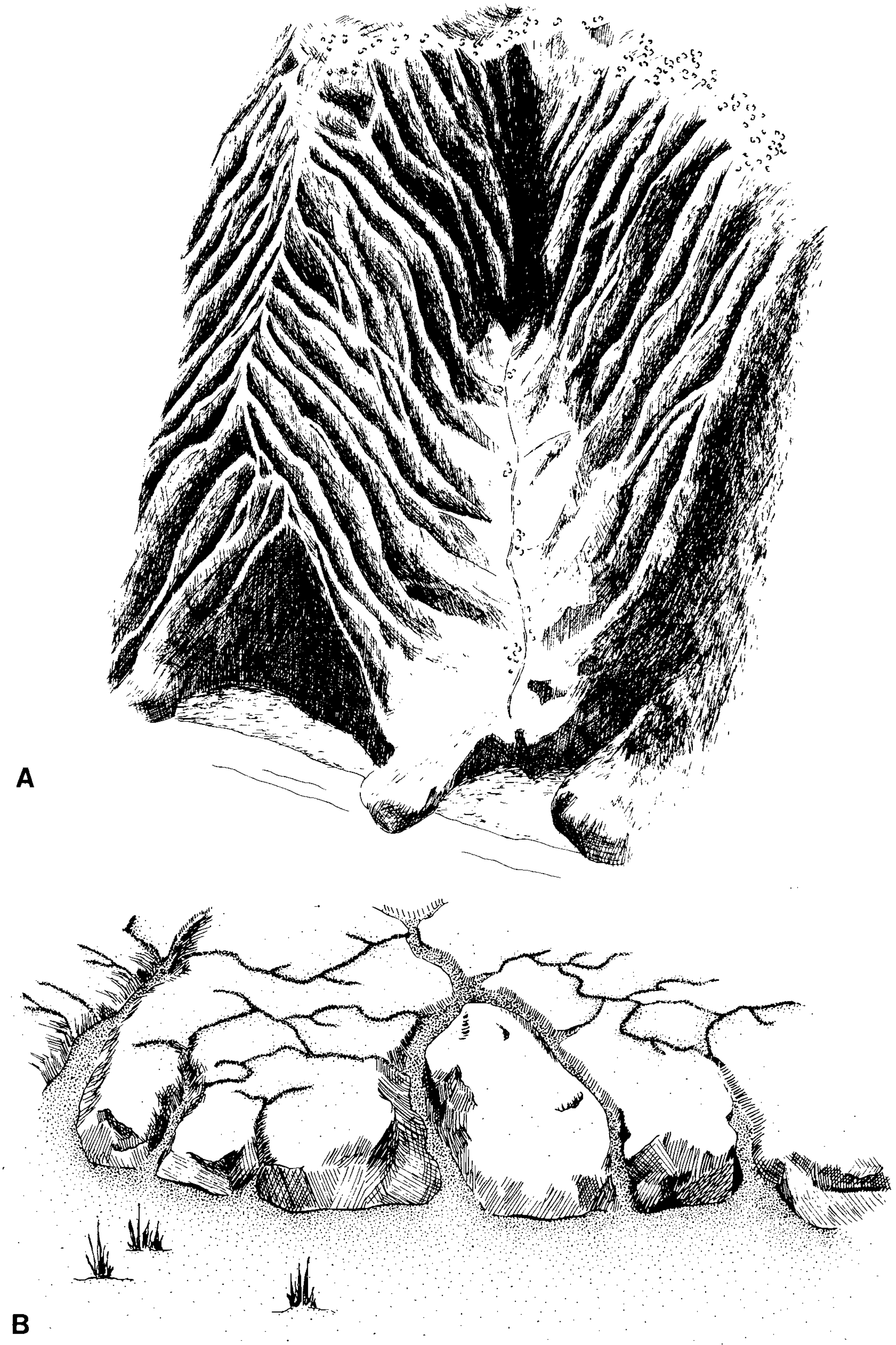
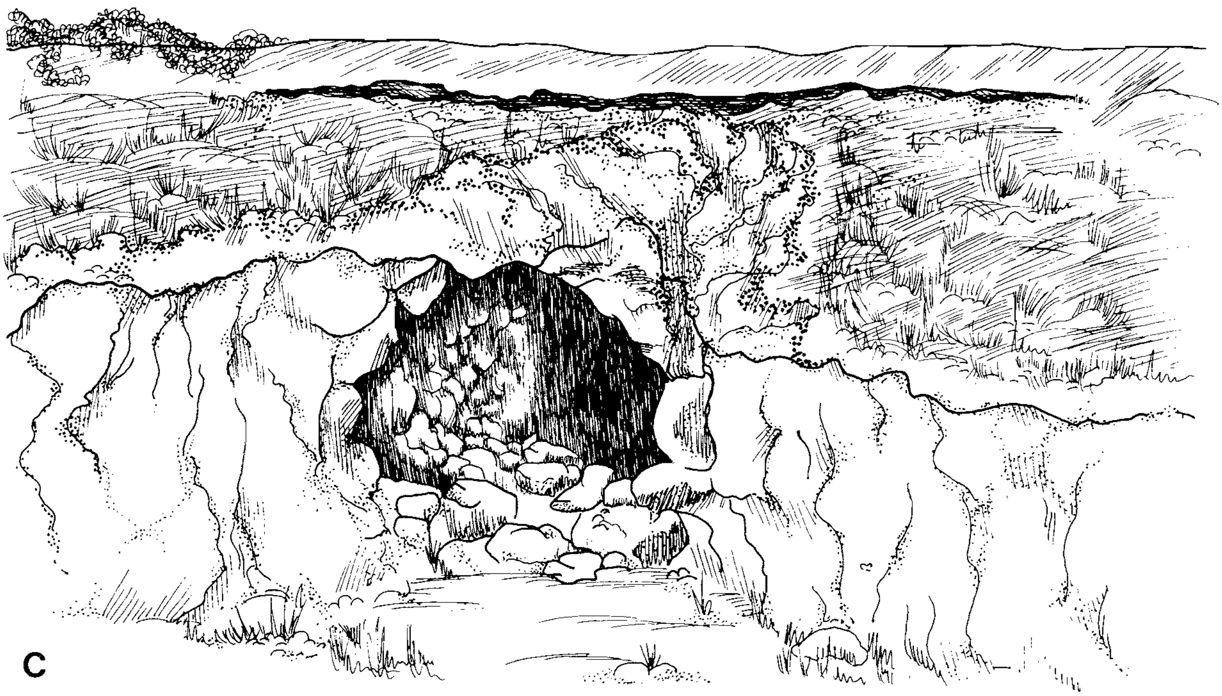


Figure 1. Schematic illustrations of major forms of erosion by water. A. Gully erosion (Scale: 1 cm = 10 or more meters); B. Rill and interrill erosion (Scale: 1 cm = 1 m); C. Tunnel erosion (Scale: 1 cm = 1 m); D. Pedestal erosion (Scale: 1 cm = 10 cm).



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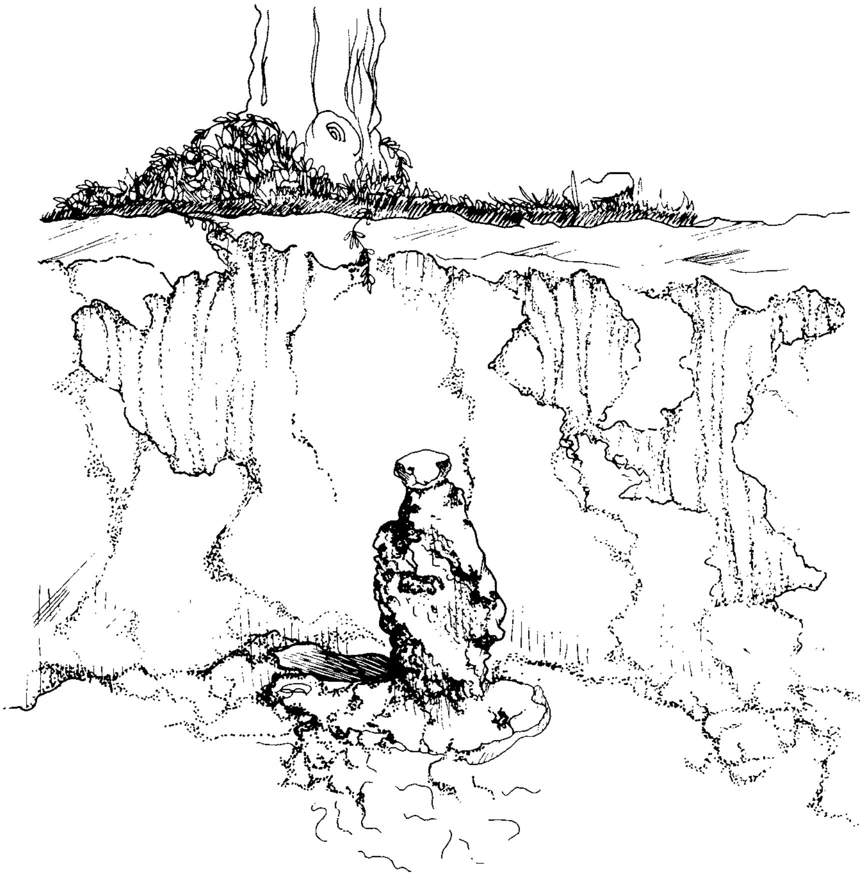

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products of soil formation. Bennett (1939) indicated that tillage operations probably increase the rate of topsoil renewal to about 30 yr/cm. This rate is nearly equivalent to 11 Tm/ha/yr (5 tons/acre/yr). This value, therefore, has often been stated as an upper limit of permissible soil loss from agricultural lands.

In considering the impact of erosion on productivity (see chap. 3), target figures for erosion control in the United States are frequently stated as 2–11 Tm/ha/yr (Wischmeier and Smith 1965). Recent trends allow for differentiation of affordable soil losses among different soils (Young 1980). Such differentiation is based on soil depth explorable by crop roots, fertility and tilth status of the subsoil, and water drainage characteristics of deeper soil layers. Conservative targets (e.g. 2 Tm/ha/yr) should be set for soils with shallow root zones and those where correction of productivity losses cannot be sustained economically.

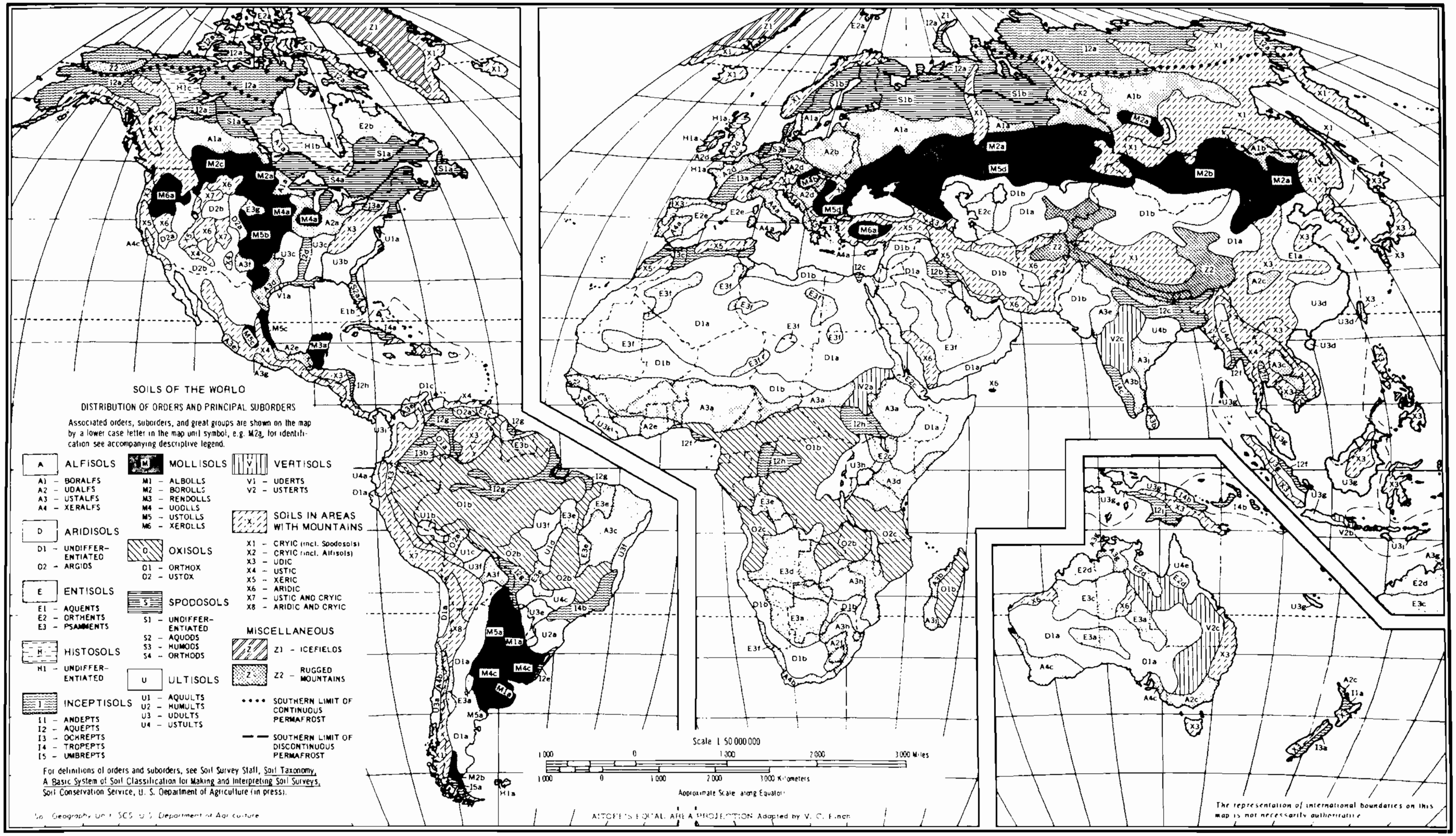
While soil loss tolerances based on reduced productivity are affected only by soil removal, tolerance limits may also be set with a view of the environmental impact of sediments during their transport or delivery to specific destination points. Historically, improvements in soil productivity, often reflected in flourishing civilizations, have been attributed to irrigation with sediment-laden flood waters (e.g. basin irrigation with Nile water during the flood season in Egypt). Recently, however, the detrimental aspects of sediments have been emphasized and incorporated into water quality criteria by various countries or states (ARS 1975*a,* 1975*b*). For this purpose, soil losses from the field and changes in sediment load of runoff water, during transport and upon delivery to destination points, must both be evaluated (ARS 1975*b;* Wischmeier 1976*a*). Although it may be argued from an esthetic viewpoint that environmental quality is low on the priority scale for developing tropical countries, there is evidence that serious economic detriments may also be associated with sediment delivery phenomena. These include uncontrolled losses of valuable water supplies, degradation of watersheds, siltation of water storage structures, burial and/or flooding of low-lying communities and productive agricultural lands, reduced effectiveness of rivers, lakes, and estuaries for sustained transportation or fishing use, as well as other problems. General use of delivered sediment as a criterion for erosion tolerance has not been fully formulated. However, the expected magnitudes (per hectare of source) are generally much smaller than the corresponding soil losses from the source (e.g. 2–11 Tm/ha/yr stated above); the relationship between the two is a function of the "sediment delivery ratio." This ratio generally decreases with increased area and steepness of land source, thus reflecting the expected redeposition of eroded sediments within large and relatively flat watersheds. Unfortunately, soil loss and delivered sediment have often been used synonymously by erosion workers for estimating soil erosion (see chap. 2).

Detailed discussions of all the impacts that need to be considered in evaluating the tolerance limits associated with soil erosion in the tropics are provided in chapter 3.

SPECIAL CONSIDERATIONS FOR THE TROPICS

The tropical (or intertropical) zone lies between the tropics of Cancer and Capricorn and includes regions that have wide differences in climatic, biological, geological (structure and age), and geomorphological properties. All of these have combined to produce a wide variety of soils, so diverse that all ten orders of the U.S. Soil Taxonomy are represented in the tropics (SCS 1975*b;* Map 2). Despite this diversity, the term "tropical soils" is frequently used by both lay and scientific personnel. Despite its lack of precision, the term is generally associated with highly weathered, red, acid, and infertile soils (Uehara 1977). This is partly justified by the occurrence of the taxonomic order Oxisols only in or near tropical regions (Map 2). Inherently, Oxisols are highly weathered, strongly structured, and well-drained soils with low susceptibility to water erosion (El-Swaify and Dangler 1977). However, erosion hazards on Oxisols and other soils of the tropics are high, by virtue of aggressive climates with highly erosive rainfall.

Although all the forms of rainfall erosion defined above occur in the tropics, the relative distribution of different forms has not been documented; nor have the relationships between abundant forms and prevailing climatic, soil, land use, and topographic conditions been determined. Information is equally lacking on tolerance limits for allowable soil losses in the tropics. Smith and Stamey (1965) reported that "normal" soil losses from well-vegetated locations on two soils in Puerto Rico ranged from 0.45 to 3.0 Tm/ha/yr. The higher value exceeded those reported for several locations in the mainland United States except for one value (7.7 Tm/ha/yr) recorded



Map 2. World soil classification in terms of the U.S. Soil Taxonomy. (SCS 1975*b*)

for forest vegetation disturbed by semiannual burning. Using soil depth and physical properties as criteria, Lombardi Neto and Bertoni (1975) calculated tolerable soil loss limits ranging from 4.2 to 15.0 Tm/ha/yr for soils apparently representing Ultisols (with argillic B horizon), Oxisols (latosolic B horizon), Lithosols, and Regosols. These appear to be within the range generally recommended in temperate regions (Wischmeier and Smith 1978).

Because of the large variability in the properties of tropical soils, a large number of tolerance limits may be calculated, each for a specific soil and criterion (such as soil regeneration rates or erosion impact on productivity). The high rates of weathering associated with tropical climates may lead to high soil regeneration rates, thus appearing to favor flexibility in tolerance limits. However, these very conditions promote high erosion hazards and depletion of crop nutrients. Furthermore, highly weathered oxidic soils are very fragile systems in which productivity may be more detrimentally and disproportionately affected by small soil losses than in their temperate counterparts. This is because the favorable nutrient and physical conditions necessary for supporting plant growth on highly weathered soils are far from uniform with depth. Rather, they are restricted to the topmost segment of the soil profile (chap. 3). Because of limited resources, the typical small farmer in the tropics is unable to invest in rectifying erosional damage to soil productivity. Clearly, therefore, erosion tolerance rates for tropical soils should not depend on soil characteristics alone. Historically, that small farmer has deserted lands with sufficiently deep soils but depleted productivity, to farm freshly cleared forest lands of high productivity. Sooner or later, as long as more land was available, the cycle would be repeated (see rationale for shifting cultivation, chap. 4). All the while, the farmer's selections of cultivable crops were necessarily restricted to those that survived best in soils of widely varying states of nutritional stress (Wright 1976), but were not necessarily nutritionally balanced or conservation effective.

Environmentally, sediments from oxidic (tropical) soils have been shown to cause more turbidity (and thus lowering of optical quality) in destination water bodies than temperate soils (Ekern 1977; El-Swaify and Cooley 1980). Therefore, if water quality at the sediment destination is to be considered, soil loss tolerances for tropical soils should be reduced accordingly. Indeed, the collective contributions of the criteria discussed above suggest that soil loss tolerances for highly weathered tropical soils should be less than for their temperate counterparts.

CHAPTER 2
EXTENT OF WATER EROSION IN THE TROPICS

APPROACHES, METHODS, AND SCALES OF SOIL EROSION ASSESSMENT

Soil erosion may be assessed by applying different methods on various scales. For the purpose of conservation-effective land-use planning, there is strong merit in assessing the extent of both existing and potential erosion. As will be discussed below, some experience in the first is required for the second.

The extent of existing erosion may be determined directly by measuring soil losses from fields (catchments) or parts thereof (subcatchments) both of which are defined by specific boundaries (Hudson 1971). Trapping and measuring the quantity of removed soil or estimating the quantity from measurable changes in soil level throughout the field are two common procedures for direct determination. The first technique has been used by most workers to determine soil losses or sediment yields in runoff water (El-Swaify and Cooley 1980, 1981). Dunne (1977*a*) applied the second technique to estimate erosion for semiarid rangelands in Kenya, using remnant vegetation and tree root exposure as indicators of surface lowering (Fig. 2). Qualitative sur-

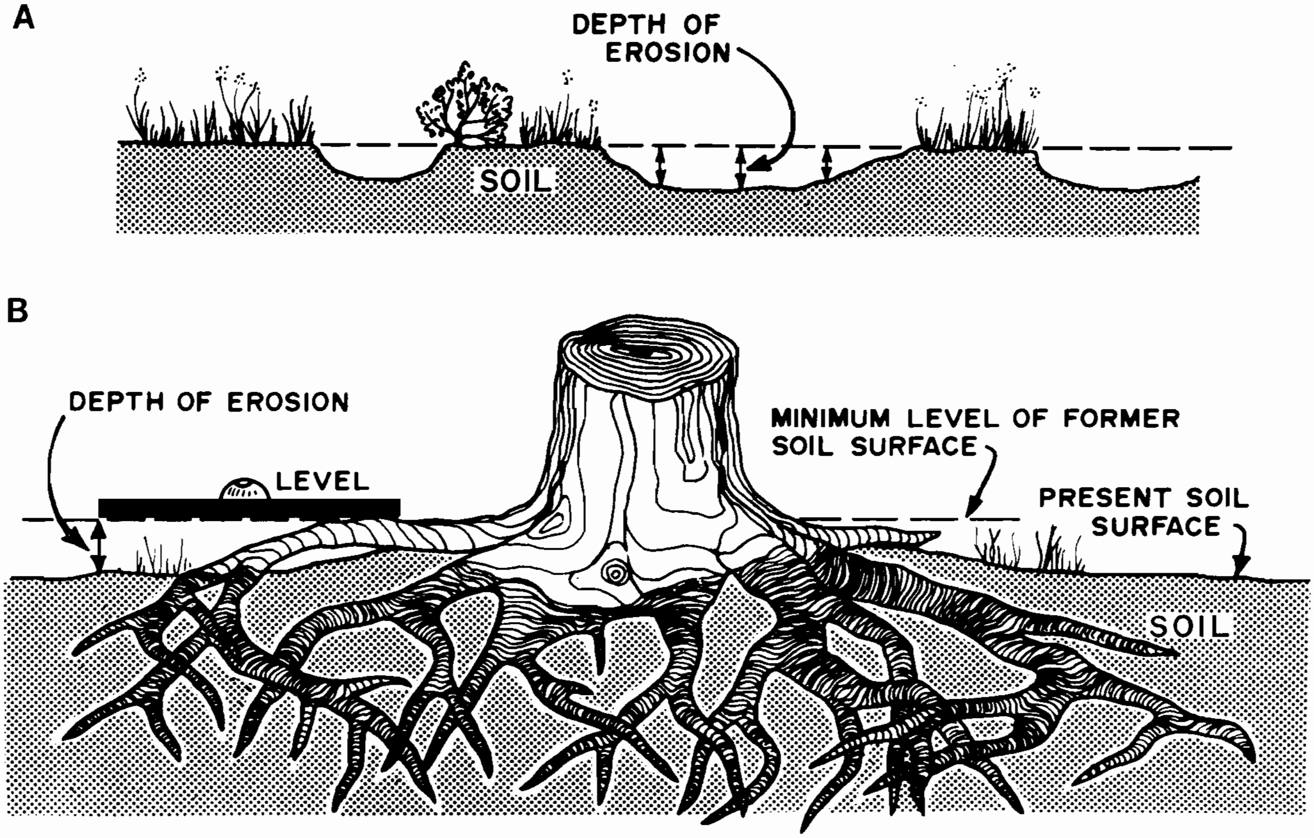


Figure 2. Measurement of erosion around vegetation. (A) Measurement of recent sheetwash erosion between vegetated remnants of the former soil surface; (B) Measurement of erosion around tree roots. (After Dunne 1977*a*)

Table 1. Classes of erosion

Class	Description
1	No apparent, or slight, erosion
2	Moderate erosion: moderate loss of topsoil generally and/or some dissection by runoff channels or gullies
3	Severe erosion, severe loss of topsoil generally and/or marked dissection by runoff channels or gullies
4	Very severe erosion: complete truncation of the soil profile and exposure of the subsoil (B horizon) and/or deep and intricate dissection by runoff channels or gullies

Source: USDA Soil Survey Staff 1951.

face reconnaissance surveys by trained personnel can also yield much information, which, although usually subjective, is valuable for differentiating the several forms of erosion—rill, interrill, and gully. In the United States and many other countries, observations of erosion trends are often made as part of standard soil surveys. The descriptive classes shown in Table 1 are commonly assigned. Rapid but qualitative observations of erosion sources, relative magnitudes, and sediment destination can also be made with considerable detail by use of aerial photography (Arnoldus 1974) or, more recently, satellite imagery (Baumgardner et al. 1978). Both can reveal erosion rates when several sets of photographs are obtained at defined time intervals. Because of their limitations on detectability, gully erosion is the primary erosion type readily identifiable by these methods. Indirect estimates of soil loss may also be made from the sediment loads of rivers, surface waterways, or reservoirs receiving runoff from defined drainage basins (Rapp 1977*a*). However, these sediment delivery data cannot be equated with soil loss data, as much of the soil eroded from the land is redeposited at the bottom of field slopes, in depressions and other land features capable of trapping the sediment as it moves with runoff, ultimately to a stream (Roehl 1962; Wischmeier 1976*b*). The problem is complicated because the sediment does not remain fully suspended once in the stream. Rather, it separates into a suspended load and a bed-load; often the first is sampled and the second ignored (Dunne 1977*a*). The ratio of "actually delivered" sediment to gross soil loss is defined as the sediment delivery ratio. Roehl (1962), working with data for the central and southeastern United States, found that the ratio varies inversely with the fifth root (0.2 power) of the total area that drains into the stream (Fig. 3). However, Rapp (1977*a*) indicated, as expected, that such a relationship is not universal. His data showed that the decrease in sediment delivery ratio with increasing drainage area was less marked for Tanzanian watersheds than those in eastern Wyoming (Fig. 4). Dunne (1977*a*) pointed out the added importance of catchment relief characteristics in determining sediment delivery ratios. This factor combines with differences in prevailing soil types and vegetation to yield site-specific trends for catchment-area effect on sediment delivery ratio. Of particular importance is the occasional observed reversal of these trends, when disproportionately higher sediment yields were obtained from large catchments than from small plots, where gully formations prevail as the major form of erosion (Heusch 1981). An additional complication of converting sediment data to field soil loss (Tm/ha) is encountered when sediment yields are measured as the volume of dredged deposits (m^3) in waterways or reservoirs. Such conversion requires the use of sediment bulk density values that are often assumed to have a single universal value (1.5 Tm/m^3)—an assumption that is far from justified. Geiger (1965, cited by Dunne 1977*a*) showed that the bulk density of reservoir sediments varies from 0.64 to 2.08 Tm/m^3 depending on composition and drying status (aeration).

Evaluation of erosion potential (risk, hazard) requires an understanding of the contribution of each of the parameters controlling the erosion process. Quantitative values for these parameters can be derived only from site studies designed to monitor the dependence of soil loss on each parameter (chap. 4). Once known, these values can be incorporated into predictive formulae (Hayes 1977; chap. 4) and used to estimate the magnitude of potential erosion

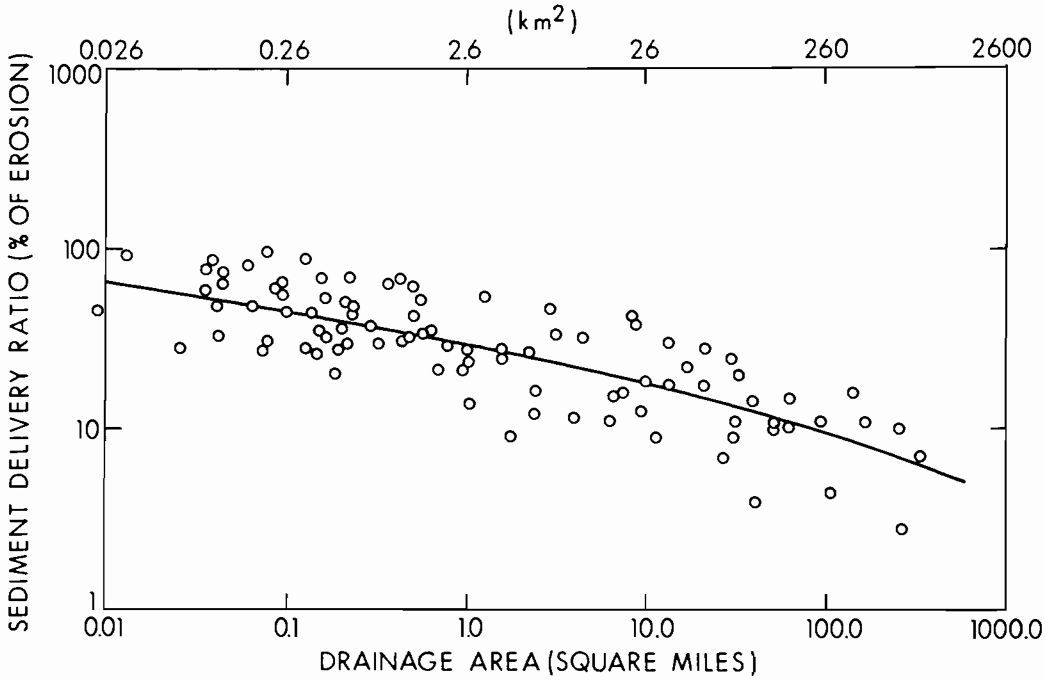


Figure 3. Relation between sediment delivery ratio and catchment size. (Roehl 1962)

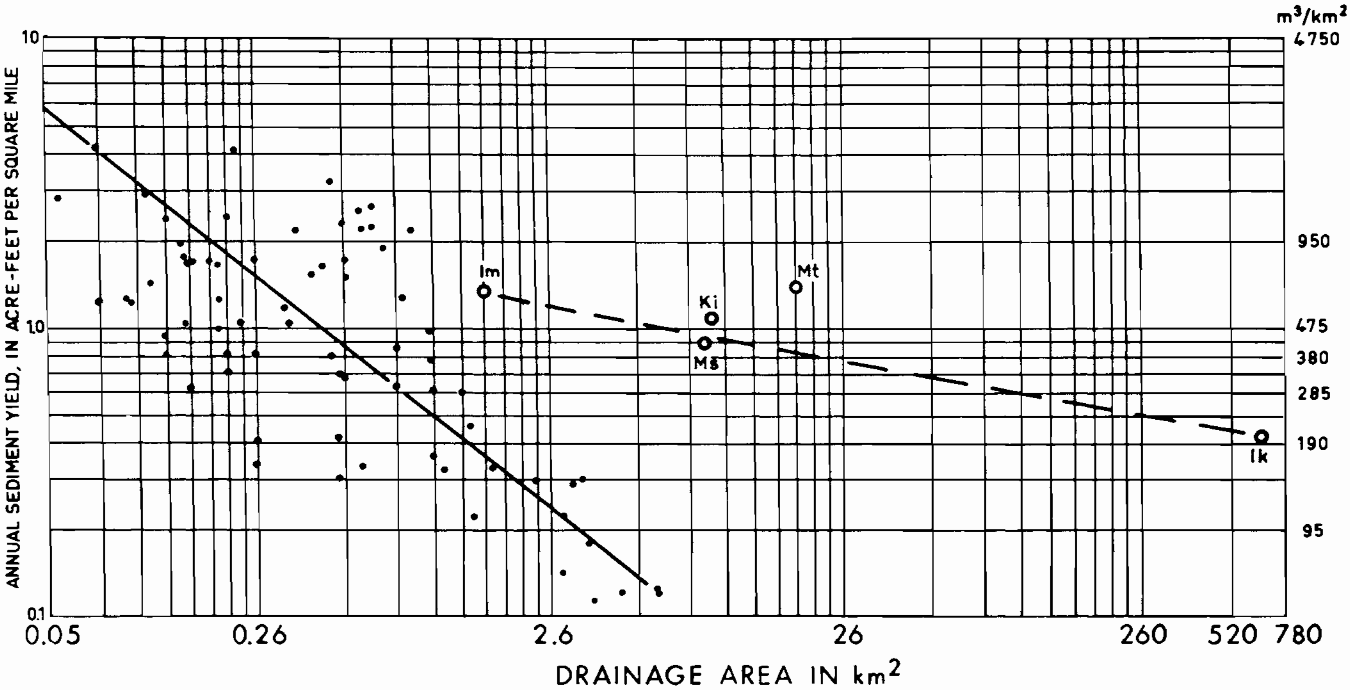


Figure 4. Relation of mean annual sediment yield to drainage area for the five catchment basins in Tanzania (open circles) compared to seventy-three semiarid basins (dots) in eastern Wyoming, U.S.A. Ik = Ikowa watershed; Im = Imagi watershed; Ki = Kisongo watershed; Ms = Msalatu watershed; Mt = Matumbulu watershed. (Rapp 1977*a*)

under specified conditions. As with actual erosion assessment, evaluations of potential erosion may be made quantitatively for specific sites, or qualitatively by assigning classes or codes of erosion hazard to different land units on a variety of scales (Arnoldus 1974). Although quantitative and specific assessments are preferable, they require long-term studies under natural rainfall conditions (Wischmeier and Smith 1978); values for certain parameters (e.g. soil erodibility and topography) may be obtained more rapidly with simulated rainfall (Dangler and El-Swaify 1976).

The scales at which erosion assessments are made range from very small (i.e. global or continental [FAO 1977*c*]) to large (i.e. concentrated on small field sub-plots [Olson and Wischmeier 1963]), with intermediate scales covering defined catchments or watersheds (El-Swaify and Cooley 1981). Small-scale assessments frequently involve whole river basins and are generally qualitative, thus tending to mask important contributions of small but seriously degraded areas. Maps based on these assessments (FAO's scale is 1:5,000,000) are of value to land-use planners and decision makers, particularly for identifying overall erosion hazards at the regional or national level (Riquier 1981). However, they are not directly useful for the formulation of plans to detect specific erosion sources, or to formulate measures to combat them, because of the site-specific and extremely variable nature of erosional processes with space and time. Only inventories based on long-term, large-scale studies involving quantitative determinations in small plots are within the detectability limits necessary to reveal variations in climatic, topographic, soil, and management causes of soil erosion at specific problem areas. Depending on the objectives of the assessment program, a combination of studies at different scales is ideal for deriving needed information. This involves an initial reconnaissance by aerial photography or satellite imagery, reconnaissance surveys of the land surface, monitoring of sediment losses from large catchments, and ultimately, measurement of soil losses from field plots or small subplots.

The numerous methods used to assess actual and potential erosion at various scales have been developed and refined in temperate regions. Subsequently, many have been applied to parts of the tropics, either directly or with some modification (Hudson 1971; Lal 1976*d*; Dangler and El-Swaify 1976; FAO 1977*c*). For the purpose of erosion assessment and prediction, one may treat erosion-causing factors as universal, but quantitative values for each must be derived for each region (mapping unit) at which they will be used (chap. 4; Wischmeier 1976*b*). On-site studies are therefore required to insure the adaptation of foreign technology to the tropics. Clearly these studies should allow for assessment of both erosion extent and causative factors. However such studies are costly, time consuming, and demand substantial requirements of trained personnel —factors that explain the limited quantitative data originating from tropical countries. In the few cases where studies have been conducted, results have not always been available for inclusion in this report due to nonpublication or nonaccessibility of documents. Information available at the time of writing is presented in the following section.

RAINFALL EROSION IN THE TROPICS—GENERAL TRENDS

It has often been stated that on a global scale the hazards of soil erosion by water are mostly restricted to the regions between latitudes 40° N and 40° S (Hudson 1971). The humid tropics are wholly within these limits and their potentially high erosion hazard largely results from the characteristic prevailing climates (Fig. 1). In addition to possible enhancement of weathering by wind and temperature factors, the humid tropics are characterized by large quantities of annual rainfall and frequent, intensive rainstorms. At the other end of the scale are the arid tropics, where rainfall is rarely capable of meeting vegetative requirements, saturating the soil, and inducing runoff. There the hazard of rainfall erosion is nearly absent, whereas wind erosion may be severe. Areas of intermediate rainfall, such as the semiarid tropics, may present a dangerously high erosion hazard during the rainy season.

Although they may serve as general indicators, climatic (specifically rainfall) characteristics alone are not sufficient for assessing total erosion hazard, which clearly depends on other factors, including the nature of the soil, topographic setting, vegetative cover, and management factors. These considerations collectively explain, for example, why the potential erosion hazard in the semiarid tropics may exceed that in the humid tropics even in the absence of human interference. At least two factors are responsible. First, the semiarid tropics lack the water supply needed to sustain the permanent vegetative cover, which is necessary for soil protection

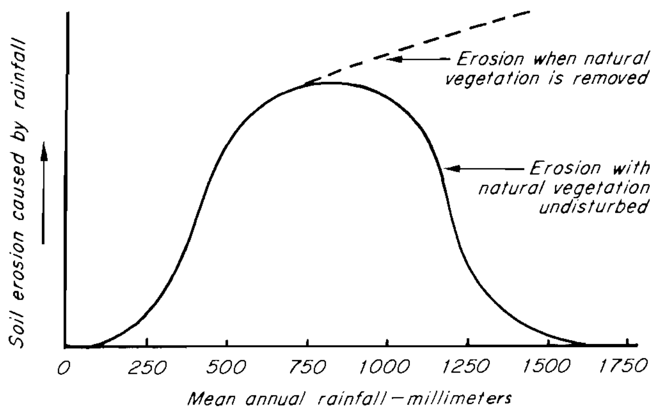


Figure 5. Changes in soil erosion trends with rainfall. (Hudson 1971)

against erosion and which characterizes the natural forestlands of the humid tropics. The sparse and fragile vegetation remaining at the end of the dry season provides little protection against erosion during the rainy (and windy) periods that follow (Rapp 1975). Secondly, the less intensively weathered soils common to the semiarid tropics (e.g. Vertisols) are inherently more susceptible to water erosion than those that prevail in the humid tropics (e.g. Oxisols) (El-Swaify 1977; chap. 4). Additional factors include the possibility that the erosivity of rainstorms prevalent in the semiarid tropics may (despite the short wet season) exceed that of those in the humid tropics. It is important to emphasize that the lower erosion hazard in the humid tropics (compared to that in regions of intermediate rainfall) exists only in the absence of human disturbance (e.g. by deforestation). When characteristically rich natural vegetation is removed, erosion caused by the large quantities of rainfall in the humid tropics will exceed that in other climatic regions (Hudson 1971; Fig. 5). The simple presence or absence of protective vegetative cover may therefore be more important than the climatic regime.

A quantitative treatment of all parameters that determine potential erosion hazards on a global scale will be developed in chapter 4.

RAINFALL EROSION IN THE TROPICS—SPECIFIC INVENTORY

Worldwide, quantitative data on the extent of ongoing soil erosion are isolated and fragmentary. However, it is known that each continent suffers accelerated forms of soil erosion and that, on a global scale, more soil is degraded by this means than any other (Riquier 1980). The damage is most noteworthy in developing countries which are located mostly in the tropics. For instance, it is estimated that 27 tons/ha of cropped soils are lost annually in the United States; in developing countries that rate is estimated to be twice as severe at 54 Tm/ha (Ingraham 1975 cited by Pimentel et al. 1976).

The serious lack of reliable data on soil degradation, by erosion and other forces, has prompted the United Nations Conference on Human Environment (held at Stockholm in 1972), to recommend that "the Food and Agriculture Organization of the United Nations (FAO) in cooperation with other international agencies concerned, strengthen the necessary machinery for international acquisition of knowledge and transfer of experience of soil capabilities, degradation, and conservation" (Riquier 1980). FAO and the United Nations Environmental Program (UNEP) have begun two assessments of the global distribution of erosion—the presently existing risk and the potential maximum risk (in the absence of such protective measures as vegetative cover and land shaping). Both are to be presented as maps at a scale of 1:5,000,000 (FAO 1977*c*), thus assuming land homogeneity within large mapping units, due to the lack of direct detailed field observations in most countries. The constraints of such small-scale maps were discussed above and are further elaborated upon by Riquier (1980).

As a beginning point of discussion, it is revealing to examine the overall rates of continental erosion. If the mechanical denudation rates given in Table 2 are used as a basis for computing erosion rates, the

Table 2. Rates of erosion of the continents*

	Area ($km^2 \times 10^6$)	Denudation Rates ($Tm/km^2/yr$) Mechanical	Chemical
Africa	29.81	47.0	25.2
Asia	44.89	166.0	42.0
Australia	7.96	32.1	11.0
Europe	9.67	43.0	32.0
North and Central America	20.44	73.0	40.0
South America	17.98	93.0	55.0

Source: Modified from Starkhov 1967, in Chorley 1969.
*From suspended sediment data from rivers.

overall sediment losses from the continents range from a low of 0.32 Tm/ha (for Australia) to 1.66 Tm/ha (for Asia). However, because these sediment losses are derived from only a small fraction of each continental area (note the vast desert areas in Africa and Australia), and are based only on suspended sediment loads in major rivers, the actual erosion rates from the source soils in the tropics may be estimated to approach or even exceed the average value of 54 Tm/ha stated above. Although the rates listed in Table 2 are, per unit area, highest for Asia and South America, it would be incorrect to rank actual erosion rates similarly, since the exact areas of lands providing erosional sediments are not known. By confining the scope to defined river basins in the tropics and using a conservative sediment delivery ratio of 0.05, we have estimated values of 0.8 to 555 Tm/ha (Table 3; Fig. 3). For the same reasons discussed above, these values are likely to be underestimates of actual soil losses from lands that are the specific sources of erosional sediments. Nevertheless, it is worthwhile to note the very probable danger signals revealed by the extremely high values for the basins of the Kosi, Damodar, Ganges, and Mahanadi rivers in India, the Red River in Vietnam and China, the Irrawaddy in Burma, the Caroni in Venezuela, and the Mekong in Southeast Asia. Although values shown for the basins of the Chao Phraya in Thailand, the Orinoco in Venezuela and Colombia, and the Amazon in South America, are relatively low, they exceed or border on what may be considered tolerable normal erosion (chap. 1). Depending on the extent of land actually eroding, these and the lower values shown for the basins of the Nile, the Congo, and the Niger are no cause for relief as they likely underestimate the real extent of soil erosion at the source. The following sections will elaborate on those tropical areas of the continents for which substantive information was available.

Rainfall Erosion in Tropical Africa

Despite large voids in available quantitative data, lack of standardization in assessment techniques, and the discontinuous nature of completed surveys, tropical Africa has been the subject of more studies, resulting in more information on soil erosion and sedimentation, than other tropical regions. Credit is due to colonial settlers who generally exploited the land by first introducing nontraditional, conservation-ineffective methods, thus generating a need for assessment of and solutions to erosion problems (Hill 1965). Currently increasing population pressures further aggravate these problems. Greenland (1977), referring to the humid tropics of Africa, stated that the "soils of these areas are generally much less productive than they might be, and if more intensive use leads to further loss of fertility and further erosion, the present potential to feed the burgeoning population of these regions will be lost."

The small-scale (1:5,000,000) mapping of present and potential degradation, including erosion, in Africa and the Near East is now nearly completed by FAO-UNEP as the first step in their global assessment of soil degradation. This mapping is based on submaps for estimated individual factors that control soil loss by water—rainfall erosivity, soil erodibility, topography, vegetative cover, and land management (Arnoldus 1980; Riquier 1980). Earlier, Fournier (1962) obtained good correlations between suspended sediment loads in rivers and streams, and combined indices of rainfall erosion hazard and topography for defined large catchments ($>2,000$ km²) on several continents (chap. 4). He used these correlations to construct a risk map of "normal" erosion for Africa south of the Sahara (Map 3). The map includes six hazard classes combined with a generalized soil classification, but soil susceptibility to erosion was not incorporated as a parameter of erosion hazard. Neither were dominant vegetation nor prevailing land use used as modifying parameters (Balek 1977). The vast majority of tropical Africa lies within the high-risk class having sediment removal rates exceeding 1,000 Tm/km²/yr (10 Tm/ha/yr). As stated earlier, sediment load figures generally underestimate actual soil erosion by a factor that depends on both catchment size and relief, as well as possible deviations from normal conditions, such as disturbance of forest vegetation. Boundaries for hazards of various classes, when assigned to different regions, may therefore have higher numerical values for actual soil loss than are shown in Map 3. Actual or potential erosion from specific field sites would be of even higher magnitude. Nevertheless the map is useful for indicating the relative magnitude of erosion by water in the absence of human interference, as well as changes in erosion that may occur following such interference.

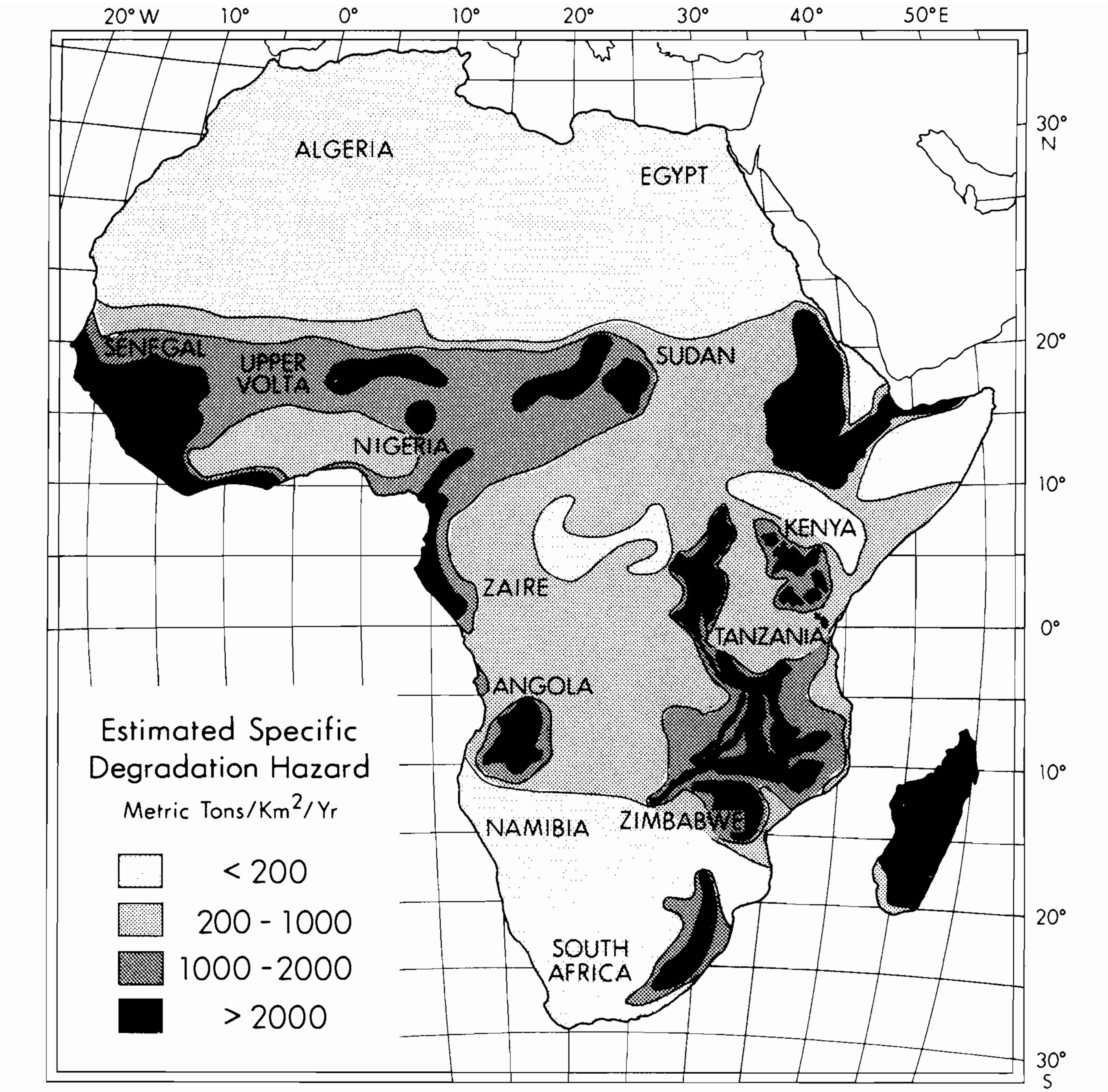
Fournier (1967), and more recently Armstrong et al. (1981), provided historical reviews of soil erosion and conservation research in Africa. A current bibliography on soil erosion by water in this continent is

Table 3. Estimated annual soil erosion within drainage basins of selected rivers of the tropics

River	Countries within drainage basin	Drainage basin (10^3 km^2)	Average annual suspended load		Estimated annual soil erosion from field*		Rank
			(Tm x 10^6)	(Tm/km^2)	(Tm/km^2)	(Tm/ha)	
Congo	Angola, Congo, Zaire, Cameroon, Central African Republic	4,014	65	16	320	3	13
Niger	Cameroon, Guinea, Dahomey, Chad, Ivory Coast, Nigeria, Niger, Mali	1,114	5	4	80	0.8	14
Nile	Uganda, Kenya, Zaire, Ethiopia, Tanzania, Sudan, Egypt, Rwanda, Burundi	2,978	111	37	740	8	12
Chao Phraya	Thailand	106	11	107	2,140	21	9
Ganges	India, Bangladesh, Nepal, Tibet	1,076	1,455	1,352	27,040	270	3
Damodar	India	20	28	1,420	28,400	284	2
Irrawaddy	Burma	430	299	695	13,900	139	5
Kosi	India	62	172	2,774	55,480	555	1
Mahanadi	India	132	62	466	9,320	93	7
Mekong	China, Thailand, Laos, Tibet, Kampuchea, Vietnam, Burma	795	170	214	4,280	43	8
Red	China, Vietnam	120	130	1,083	21,660	217	4
Caroni	Venezuela	91	48	523	10,460	105	6
Amazon	Bolivia, Brazil, Ecuador, Colombia, Peru, Venezuela	5,776	363	63	1,260	13	11
Orinoco	Venezuela, Columbia	950	87	91	1,820	18	10

Source: Modified from Holeman 1968. The indicated sediment losses per unit land area were calculated independently from data given in the first two data columns.

*Adjusted according to a sediment delivery ratio of 0.05 from Figure 5.



Map 3. Fournier's map of normal erosion risk in Africa south of the Sahara. (After Fournier 1962, modified)

now under preparation (Armstrong, Dangler, and El-Swaify). Following is a documentation of available information from various regions of Africa. By necessity, much of the treatment is qualitative due to serious lack of quantitative data on existing and potential rainfall erosion at specific locations.

Southern Africa and Madagascar

Accelerated erosion by water is recognized and considered a serious and urgent problem in the steep uplands and arid savannah of southern Africa. According to FAO (1965): "Damage from erosion is most severe in the territories of Swaziland, Basutoland [Lesotho], and Bechuanaland [Botswana]. . . ." Later, Hance (1975, cited by Eckholm 1976) confirmed that "The number one problem facing Lesotho is soil erosion which, despite (conservation) efforts extending over many years, continues to destroy increasing acreages." In neither report was the exact acreage affected or the quantitative degree of destruction documented. Concern for soil erosion in Swaziland is illustrated by the watchwords "Soil is our most important resource—help conserve it" that are printed on all official government stationery. Here again, little information describing the extent and severity of the problem is available. Similarly, current information is not available concerning the extent of erosion in Mozambique or Angola.

Soil erosion and conservation in Zimbabwe (Rhodesia) have been the subject of extensive studies for many years. In reporting a technique of gully survey from aerial photographs, Keech (1968) indicated the existence of an erosion survey of the whole country at a scale of 1:1,000,000 (as yet unavailable in published form). Table 4 shows the estimated extent of gully erosion, as presented by him, for several settlements within the country. Sheet and rill erosion were not documented separately as they were associated so closely with gullying. Keech concluded that the erosion conditions of the Intensive Conservation Areas (ICA) were "favorable" while those in the Tribal Trust Lands (TTL), occupying about 162,000 km² or 41 percent of Zimbabwe's total area, varied greatly. In the report, a length of 10,999 yards (10,056 m) of gullies per 1600 acres (648 ha) is considered to be the lower limit for severe erosion. Stocking (1971, 1972) believed that high population density and intensive grazing, rather than cropping, enhanced the frequency of gully formation. However, his data (Fig. 6) show that the relief characteristics of his study areas were different. His conclusions confirmed other observations that erosion from localized areas is greatly enhanced in arid and semiarid rangelands that have been denuded by excessive trampling by cattle gathered for dipping, watering, and so on. Hudson (1964*a*) presented a model calculation which showed that denuded areas may contribute one half of the total soil loss from rangelands. Damage caused by constant trampling is generally attributed to accelerated breakdown of soil aggregates. The migra-

Table 4. Percentage of land area of various agricultural settlements affected by various degrees of erosion

	Erosion class (Yd/1,600 acres*)							
Settlement	0	1-2,999	3,000-6,999	7,000-10,999†	11,000-18,999	19,000-25,999	26,000-32,999	>33,000
Chibi TTL‡	23	41	29	2	5	--	--	--
Chilimanzi TTL	8	29	41	19	3	--	--	--
Chinyika catchment	56	40	4	--	--	--	--	--
Gutu TTL	19	78	2	1	--	--	--	--
Mashaba TTL	0	38	45	15	2	--	--	--
Mtoko TTL	0	1	10	16	34	20	13	6
Sabi North TTL	7	41	33	11	8	--	--	--
Selukwe TTL	0	25	49	25	1	--	--	--
Tokwe ICA§	74	25	1	--	--	--	--	--
Turgwe catchment	45	41	13	1	--	--	--	--
Victoria TTL	9	55	19	11	6	--	--	--

Source: After Keech 1968.
* Expressed as yards (0.91 m) of gully incidence for square land units each with an area of 1,600 acres (≈670 ha).
† This figure represents the level at which erosion is classified as severe.
‡ TTL = tribal trust land.
§ ICA = intensive conservation area.

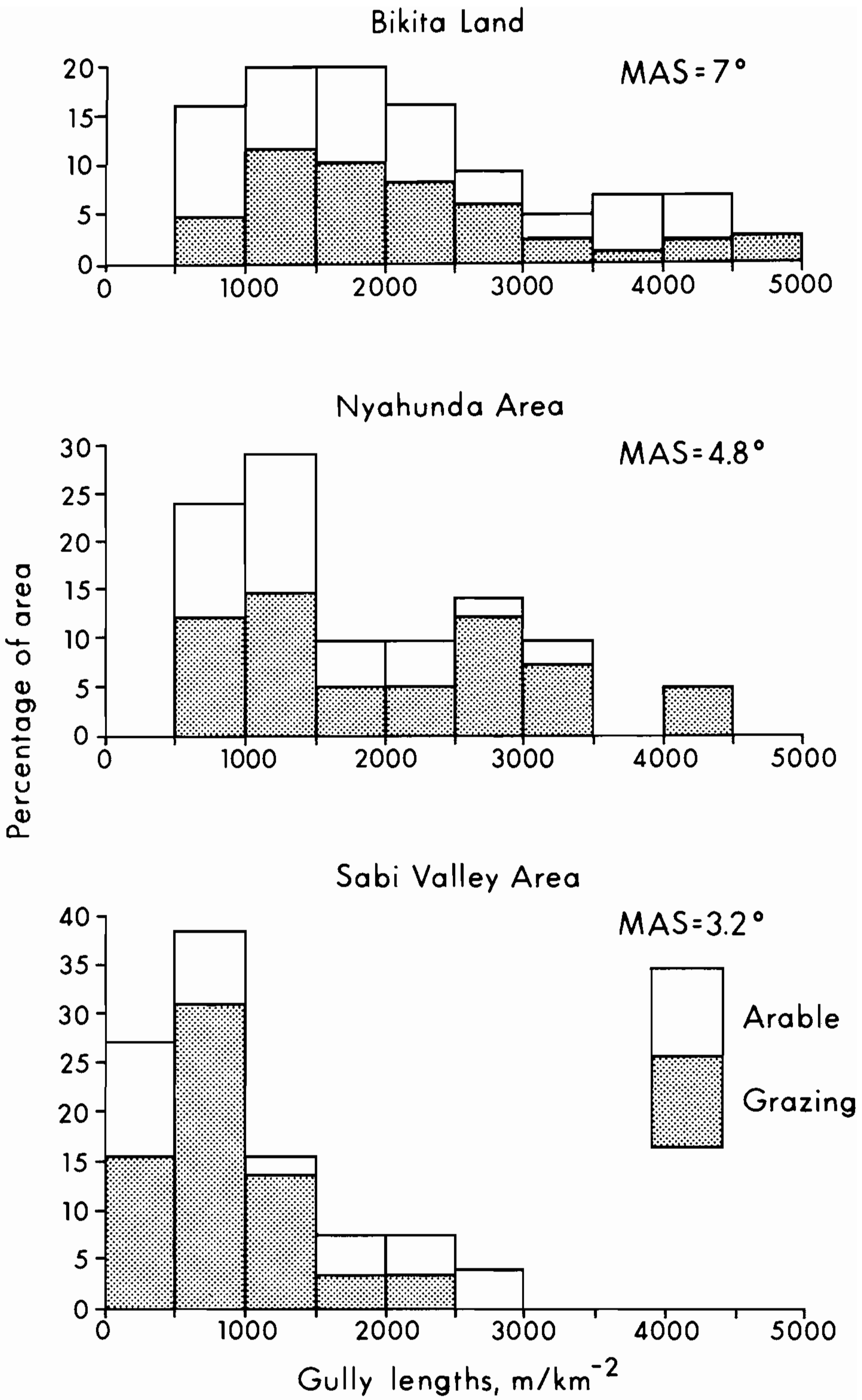
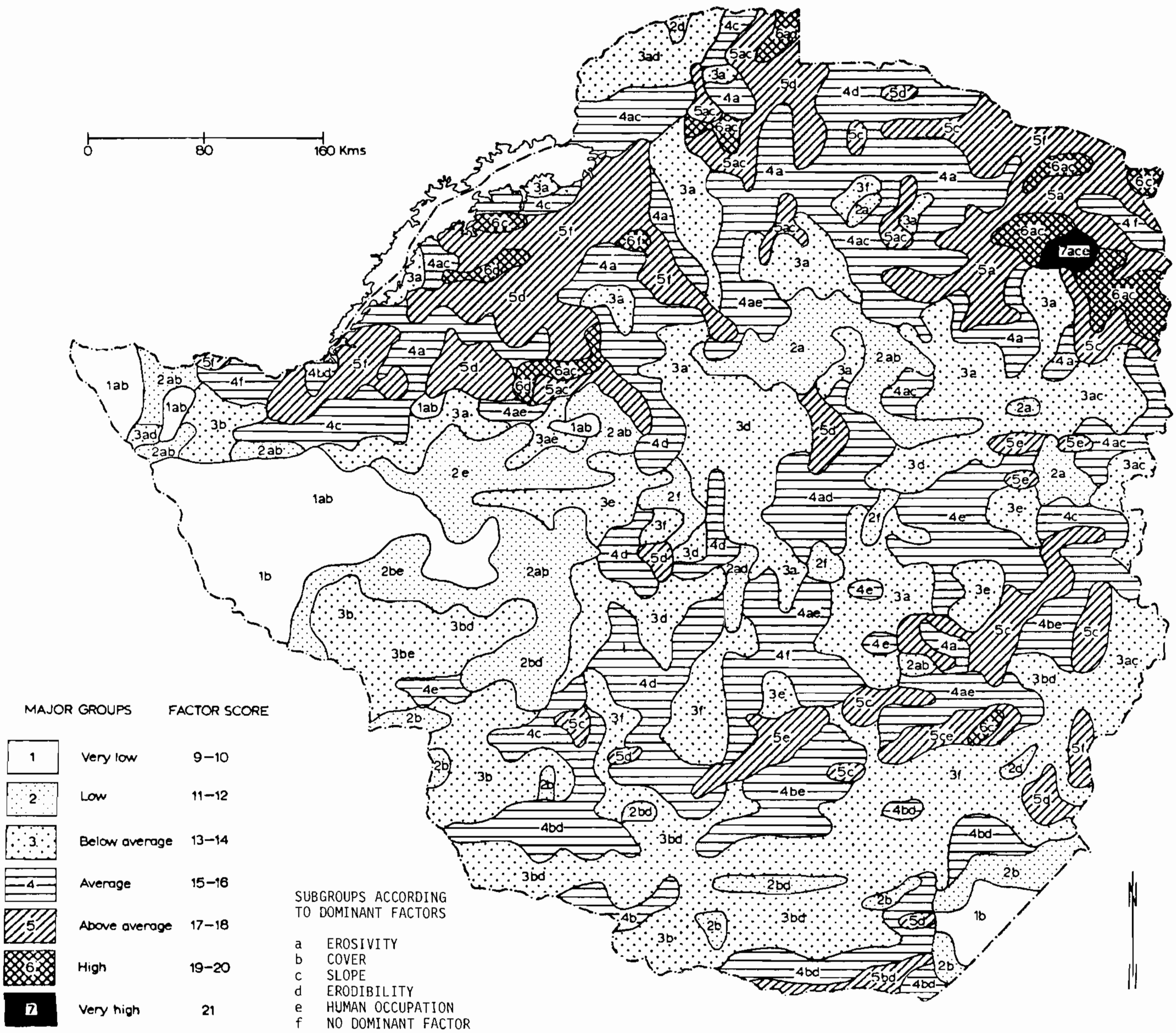


Figure 6. Comparison of the frequency of gullies from three types of land tenure in Zimbabwe (Rhodesia). MAS represents the mean average slope within each area. (After Stocking 1972)

tion of particles (Walters 1955) causes subsequent sealing of the soil surface and, ultimately, greater runoff and higher soil loss. Furthermore, reduced infiltration, together with disturbed and diminished topsoil, reduces the available soil water supply, causing a drastic reduction in protective vegetal cover. By combining the potential contributions of rainfall erosivity, vegetal cover, slope, soil erodibility, and human occupation, Stocking and Elwell (1973*b*) compiled an overall map of soil erosion hazard in Zimbabwe (Map 4). Parameters for some of these factors were evaluated quantitatively, but others were qualitative due to limited data (Table 5). Map 4 resulted from the assignment of composite-score distributions to individual causative factors. Although it shows relative hazards for various regions, it does not provide quantitative estimates of soil loss, nor does it identify the likely form of erosion. The map does show that significant erosion hazards prevail over a sizeable area of Zimbabwe, a conclusion that is likely also valid for surrounding countries in the region, namely Botswana, Mozambique, and Zambia (for which no such data are available). The Zimbabwean works cited above are among the very few in which population density and activity are considered in assessing erosion hazard.



Map 4. A map of soil erosion hazards in Zimbabwe (Rhodesia). Factor scores used to divide major groups were obtained by adding all the scores for individual categories as shown in Table 5. (After Stocking and Elwell 1973*b*)

Table 5. Explanation of major categories of potential hazard shown in Map 4

Category	Score	Erosivity (joules-mm m^2/hr)	Cover(mm of rainfall) and (%)	Slope (degrees)	Erodibility	Human occupation
Low	I	< 5,000	> 1,000 7-10	0-2	Ortho-ferralitic regosols	Extensive European ranching, National Parks, or unreserved
Below average	II	5,000-7,000	800-1,000 5-8	2-4	paraferralitic	Most European farms
Average	III	7,000-9,000	600-800 3-6	4-6	ferasiallitic	Low density TTLs† (≤ 5 persons/km^2) and APAs‡
Above average	IV	9,000-11,000	400-600 1-4	6-8	siallitic vertisols lithosols	Moderately settled TTLs (5-30 persons/km^2)
High	V	> 11,000	< 400 0-2	> 8	noncalcic hydromorphic sodic	Densely settled TTLs (> 30 persons/km^2)

Source: After Stocking Elwell 1973b.
* Cover, Erodibility, and Human occupation are tentative and cannot as yet be expressed on a firm quantitative basis.
† TTL = tribal trust lands.
‡ APA = African purchase areas.

The island of Madagascar has been described as "one of the regions of the world most prone to continuing soil erosion" (Rougerie 1965 cited by Le Bourdiec 1972). This is well confirmed by Map 3, in which most of the island is placed in the top two erosion hazard classes proposed by Fournier (1962). Le Bourdiec (1972) also stated that "the island has been termed the 'Red Island' " by those impressed by the reddening of the surrounding sea with erosional sediments resulting from frequent and large ravines (gullies) cutting into the lateritic slopes. Serious erosion is known to cover nearly three quarters of the island's surface, largely because the morphoclimatic balance has been upset by deforestation and the burning of grazing land. Accelerated erosion takes place either in superficial or cirque (cavity) forms. The first prevails on the surface of the crystalline highlands, in volcanic areas, and in the sedimentary basins. It may be laminar (sheet erosion), linear (rill and gully or ravine erosion), or may occur as mass movements similar to landslides. Cirque or cavity formations in the landscape are termed "lavaka" and prevail in the thick strata of the products of severe weathering (such as lateritic clays) on those highland slopes that are devoid of vegetative cover but are not hardened due to exposure. Both ravines and "lavaka" cause rapid and widespread catastrophic disturbances of the natural environment (Le Bourdiec 1972).

Eastern Africa

Despite the scarcity of published information dealing directly with soil loss, sediment load, or land condition, the extent of soil erosion problems in East Africa can be judged from other available evidence. In an overview of erosion hazards in this region, Ahn (1977) indicated that erosion hazard assessment is particularly complex due to great variations in altitude, climate, soils, and farming systems. Of these factors, he considered the farming system to be the most important as it determines the extent of vegetative cover that protects the soil against erosion at critical times of the year. While shifting cultivation is generally presumed to reduce erosion by virtue of mixed cropping, discontinuous farm patches within well-protected forest lands, extended harvesting periods, and abundance of weeds, the authors detected conflicting data concerning the relative merits of perennial tree crops over annuals. (See chap. 4).

In Kenya, where nearly 70 percent of the country consists of arid lowlands utilized as rangelands, erosion problems prevail in the highlands where lands are cultivated intensively, the rainfall is sufficiently heavy, and topography is steep (Ahn 1977). Were it not for the low susceptibility of soils (such as the Kikuyu series—an Oxisol) erosion would be considerably more severe. The National Environment Secretariat (NESK 1976) stated that "erosion is an obvious problem and lack of a substantial remedy taken in the future can be preceded [*sic*] by nothing but a catastrophe." The same report carried a warning by the executive director of the United Nations Environmental Program that Kenya is headed for catastrophe unless immediate action is instituted to safeguard the environment. The report indicated that all highland districts of Kenya are experiencing intolerable erosion and that conservation activities are urgently needed. One reason for the problem was stated as the "maximum utilization of land [which] has left most surfaces completely unprotected by [vegetative] regeneration apart from the coverage provided by the crops in season." Currently, cultivated areas that were once forested are contributing 12 million tons of sediment per year to the Tana River in central Kenya. Rainfall erosion from heavily grazed rangelands in eastern Kenya contributes a further 12 million tons to the eastern Tana River. Thomas (1974, cited by Ahn 1977) concluded from air-photo analysis that between 1948 and 1972, in the Machakos district (with bimodal annual rainfall totalling 820 mm) the worst erosion occurred not on cultivated cropland, but on the steeper areas denuded by overgrazing and trampling. In a follow-up study, a team from the University of Nairobi (1977) noted that lands under both cultivation and grazing were subject to serious erosion problems; cultivation prevailed in the lower zones while grazing prevailed on the higher, steeper zones of the district. The lack of adequate crop cover at the beginning of both rainy seasons (beginning in February and October) is mostly responsible for water erosion in the Machakos and regions of semiarid climate. Dunne (1977*b*) described techniques for estimating soil loss from semiarid rangelands of Kenya from surveys of both suspended sediment contents of rivers and land-surface lowering. Figure 7 shows the relative magnitudes of sediment yields resulting from four different land uses. Grazing led to the greatest sediment yield for a given quantity of runoff. Later, Dunne et al. (1978*b*) estimated that soil erosion rates under cover in the wet highlands vary between 0.18 and 0.30 Tm/ha/yr, approximately the same as the equilibrium rate of soil formation under these conditions. In contrast, they estimated sediment yields from catchments in the semiarid southern zone, where the soil formation rate is less, at 0.5 to 1.4 Tm/ha/yr even under very light grazing pressure. Recent acceleration of erosion rates to 1.08 to 200 Tm/ha/yr has been noted as a result of increased grazing, and probably of a recent weather pattern consisting of several years of drought followed by several years of heavy rainfall. Figure 8 shows the predicted rate of spreading of stripped land, which currently comprises less than 1 percent of the landscape, both at present observed erosion rates and at long-term average rates (Dunne, Dietrich and Brunengo 1978). In a separate study, Dunne, Brunengo, and Dietrich (1978) estimated geologic erosion rates in Kenya for defined times within the Cenozoic period (Table 6) and detected a likely increase in rate to 0.0029 cm/yr (0.79 Tm/ha/yr) during the late Tertiary and late Quaternary times. This rate contrasts remarkably with the current high rates indicated above, particularly under heavy grazing.

Rapp, Murray-Rust, et al. (1972) described the situation in Tanzania in similar terms. Based on their field studies and compilation of evidence collected in the recent decades by other workers, they gave clear examples of very high erosion rates and rapid loss of water storage capacity in reservoirs. The need for soil and water conservation measures in semiarid Tanzania is therefore as vast and urgent as in Kenya. Temple (1972*b*), based on field-plot studies at Mpwapwa, gave indications of the seriousness of erosion in central Tanzania but gave no measure of the areal extent of the problem. Under average precipitation of 620 mm, his results showed high runoff rates and associated soil losses of nearly 137 Tm/ha/yr (98 m^3/ha, assuming a bulk density of 1.4 Tm/m^3) in bare uncultivated plots, and 119 Tm/ha/yr for bare, flat, but cultivated plots. Crop cover and protective land shaping reduced these

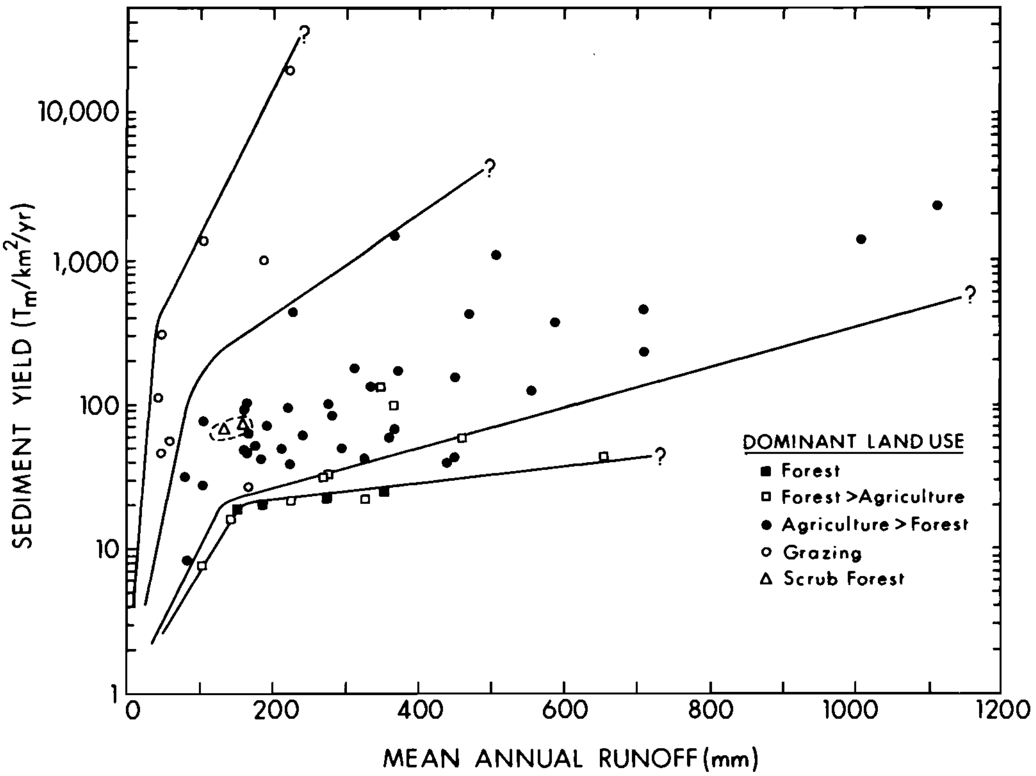


Figure 7. Sediment yields observed under various land use patterns in the semiarid rangelands of Kenya. (After Dunne 1977*b*)

losses, but they remained as high as 73 Tm/ha under bulrush, millet or sorghum. Temple considered these results applicable not only to Mpwapwa but also to a probable total of 3 million hectares of similar semiarid, low fertility lands in this region, called "cultivation steppe." These lands are dominated by derived vegetation, where the natural vegetation has been destroyed and replaced with cultivated crops or bush and grass fallow. Temple concluded that these data "demonstrated extremely severe losses of soil and water associated with natural vegetation clearance, cultivation, and overgrazing."

Concern over watershed and reservoir performance has been the major focus of studies reported by Rapp, Murray-Rust, et al. (1972) and subsequently by Rapp (1975, 1977*a*, 1977*b*). Sediment deposition in reservoirs and reconnaissance soil erosion surveys were monitored for seven watersheds, four at Dodoma in central Tanzania (considered typical of large semiarid areas of interior Tanzania in terms of physical environment); one near Arusha in northern Tanzania (also semiarid); and two partially deforested watersheds within the Uluguru Mountains in the east (with high precipitation). Table 7 shows the results of their study.

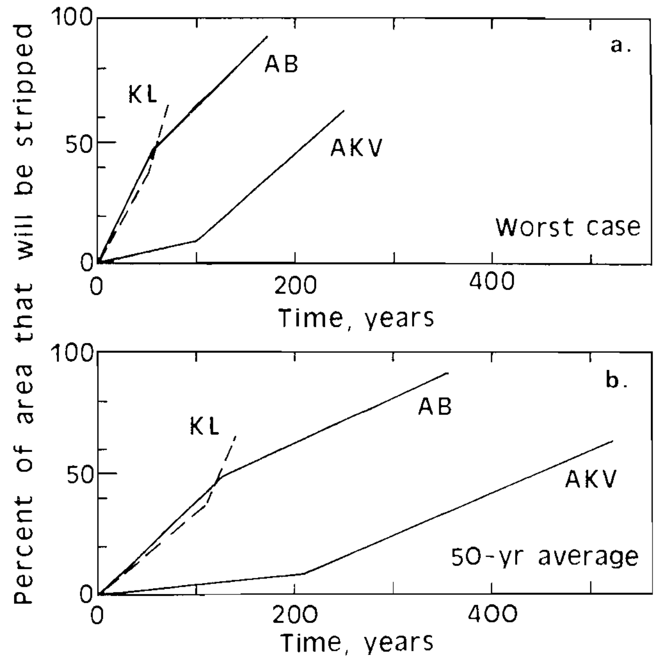


Figure 8. Extent of land that will have its soil cover removed completely within various periods of time in three study areas in Kenya: (a) assumes the "worst case" conditions of erosion rates from the past 15 years continuing into the future; (b) assumes the continuation of the average erosion rate from the past 50 years. AKV = the area of volcanic rocks on the Athi-Kapiti Plains; AB = basement schists and gneisses around Amboseli; KL = hillslopes on the Kilimanjaro lavas. (After Dunne et al. 1978*b*)

Table 6. Estimates of average Cenozoic erosion rates in Kenya

	Age (million years)	Duration (million years)	Average difference in elevation (m)	Rate of erosion (cm/yr)
End-Cretaceous and sub-Miocene surfaces				
S. Kenya	64-24	40	284	0.0007
W. Kenya	64-24	40	360-460	0.0009-0.0011
N.E. Kenya	64-24	40	335	0.0008
Sub-Miocene and late-Tertiary surfaces				
S. Kenya	24-4	20	141	0.0007
S.E. Kenya	24-4	20	152	0.0008
N. Central Kenya	24-4	20	244	0.0012
E. Kenya	24-4	20	152	0.0008
Late-Tertiary and late-Quaternary surfaces				
S. Kenya	4-Recent	4	116	0.0029

Source: After Dunne, Brunengo, and Dietrich 1978.

The estimated soil loss rates for these catchments were not corrected for intermediate deposition. Table 7 also shows results of soil loss studies on small, 50 m², field plots (Temple 1972). As expected, the rate of erosion from these plots far exceeded that from catchments. Rapp, Murray-Rust et al. (1972) noted that soil losses in the semiarid areas generally occurred as sheet wash and to a lesser extent as gullies. They provided detailed descriptions of erosion features, relief, soils, vegetation, and land use for each of the study catchments. Table 8 is a summary of their areal inventory for the Matumbulu, Msalatu, and Imagi catchments. Based on another field-plot study located in the high rainfall area (1969 mm/yr) of the Uluguru Mountains, Temple and Murray-Rust (1972) confirmed that current agricultural practices (of cultivation of steep slopes with inadequate conservation measures) are "destructive of the soil."

Confirming the above observations Christiansson (1972) described the physical characteristics, land use, and erosion evidence in the Kondoa, in the same semiarid area of central Tanzania. He observed the region as intensively cultivated in places, generally overgrazed, and completely denuded of vegetation in some parts. Sheet and gully erosion were extensive, with resultant heavy accumulation of sediment in waterways and lakes. Another erosion and sedimentation study of the Kisongo catchment, near Arusha, was reported by Murray-Rust (1972). This author estimated that 14.6 percent of a catchment area of 9.3 km² was suffering from severe sheet erosion, which was estimated to supply 85 percent of the sediment delivered to the catchment's reservoir (Table 9).

Table 9 also indicates the extent of gullying, and Map 5 shows strong evidence that the serious linear form was associated with the movement patterns of excessively stocked cattle. In contrast to the above semiarid areas, catchments in the partially deforested Uluguru Mountains covering 1500 km² were found to be subject to three main forms of erosion—sheet and rill erosion, small but numerous debris slides and mud flows, and (rarely) a large single landslide (Rapp 1975). On 23 February 1970, the Mgeta catchment, which has an area of 20 km², experienced a rainstorm that yielded 100 mm of rain in two hours and triggered more than a thousand small landslides and mudflows (Temple and Rapp 1972); the estimated recurrence interval for such

Table 7. Soil denudation rates in seven catchment basins in Tanzania (1-7), compared with data from one set of soil erosion plots (8)

Catchment						
Location	Area (km^2)	Relief Ratio*	Period/ date	Sediment yield (Tm/ha/yr)	Soil denudation rate† (mm/yr)	Expected life of reservoir‡ (yr)
1. Ikowa	640	0.015	1957-69	2.92	0.20	30
			1957-60	5.43	0.36	
			1960-63	2.90	0.19	
			1963-69	1.67	0.11	
2. Matumbulu	18.1	0.058	1962-71	10.90	0.73	30
3. Msalatu	8.7	0.045	1944-71	6.09	0.41	110
4. Imagi	1.5	0.076	1930-71	9.02	0.60	190
5. Kisongo	9.3	0.040	1960-71	7.22	0.48	25
			1960-69	6.69	0.45	
			1969-71	9.60	0.64	
6. Morogoro	19	0.235	1966-70	3.90	0.26	n.a.
7. Mgeta-Mzinga	20§	0.214§	23/2/70	202	14	n.a.
8. Mpwapwa			1933-35			n.a.
Bare plot	50 m^2	0.066		147	9.8	
Cultivated plot	50 m^2	0.066		78	5.2	
Grass-covered plot	50 m^2	0.066		0	0	

Source: Modified from Rapp, Murray-Rust, et al. 1972; and Temple 1972 b.
* Relief ratio is maximum relief of catchment divided by length.
† Denudation rates are based on reservoir sedimentation: For catchments with reservoirs (1-5), on suspended sediment sampling; for catchment 6, from streams; for catchment 7, on volume of erosion features. Average dry bulk density of sediments and soils is estimated at 1.5.
‡ Expected life of reservoir until 100% filled by sediments; economic life is shorter.
§ Approximate only.

storms is 2-10 years. In the Morogoro catchment (19 km^2), soil erosion estimates were made from suspended sediment load in the river, small plot surface lowering surveys, and field reconnaissance (Rapp, Axelsson, et al. 1972). Data showed only light erosion from rainforest areas, increasing losses from grass to bush fallow, and severe soil loss from croplands, on both steep mountain and moderately sloping foothill areas (Table 10).

The extent of soil erosion in Uganda has not been assessed quantitatively. Some general observations were given by Ahn (1977), who noted that protection of arable lands is generally adequate, but serious erosion is common on the steep cultivated slopes of the Ruwenzori Mountains and in the West Nile district. Ahn indicated that the coarse sandy loams covering large areas of central and northern Uganda are "liable to rain-splash erosion"; gullying often follows. Southern Uganda is believed to suffer more from sheet erosion, with gullies less common on its clayey soils. The East Karamoja district has been subjected to much soil compaction and overgrazing, which have led to severe erosion. The district is now marked by widespread sheet erosion and spectacular gullies; according to Ahn, there has been a change to a drier type of steppe vegetation within living memory.

Readily available information on the extent of soil erosion in Ethiopia and Somalia is similarly scarce. However, it is clear from Map 3 that most regions of Ethiopia and the northern part of Somalia fall within the highest erosion hazard class in Africa, reflect-

Table 8. Areal inventory of landforms, land use, and soil erosion in the catchments of Matumbulu, Msalatu, and Imagi reservoirs (Tanzania). The analysis is based on interpretation of aerial photographs of 1960

	Matumbulu	Msalatu	Imagi
Total area (km^2)	18.12	8.67	1.49
Number of homesteads	87	4	0
Areal percentage			
Inselberg	27.2	19.4	51.0
Cultivations	22.3	5.9	1.3
Gully erosion	16.8	22.3	4.6
Sheet erosion	8.4	12.8	14.6
Sheet erosion plus marked gullies	1.5	5.9	4.6
Sandy rivers	0.5	0.2	0
Sand fans	1.0		
Reservoir	0.5	1.4	3.3
Pediment slopes with slight erosion	21.8	32.1	20.6
Total percentage	100.0	100.0	100.0
Gullying on inselberg area (percent)	5.4	2.9	2.4

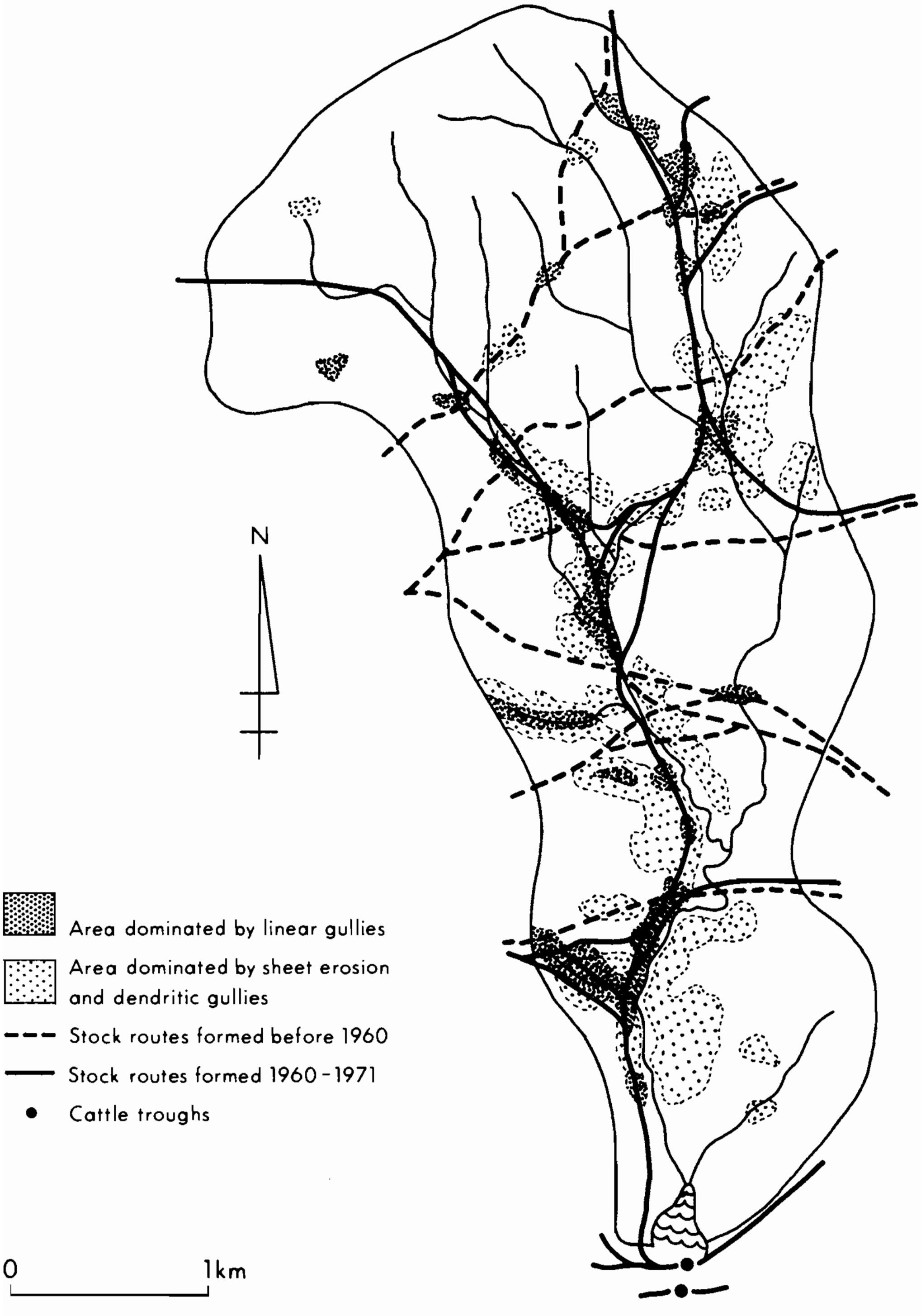
Source: After Rapp, Murray-Rust, et al., 1972.

Table 9. Estimated extent of severe sheet erosion and gully volumes, Kisongo catchment, Central Tanzania, April 1970

				Gully volumes (m^3)			Gully erosion rate per year*	
Section	Area (km^2)	Sheet erosion (km^2)	Sheet erosion (%)	Linear	Dendritic	Total	(m^3/km^2)	(Tm/ha)
Northern	5.76	0.60	10.4	1185	665	1850	32	0.48
Central	1.91	0.36	18.8	1460	1395	2855	149	2.24
Southern	1.63	0.40	24.4	1525	930	2455	151	2.67
Total	9.30	1.36	14.6	4170	2990	7160	77	1.16

Source: After Murray-Rust 1972.
*Average rate for 1960-1970.

ing the contributions of rugged terrain and high precipitation to the problem. Eckholm (1976) indicated that the Amhara Plateau—the part of the East African highlands that constitutes most of Ethiopia—may be mistakenly called a plateau. Although it rises abruptly to nearly 2000 m above the surrounding arid plains, included within this plateau are mountains that rise above 4500 m, as well as steep gorges and valleys that constitute one of the "most erosion-prone areas on earth." From here, the legendary, reliable removal of silt by the Blue Nile and other major tributaries occurs annually, for ultimate deposition on the flood plain of the Nile. Eckholm argues that when Herodotus called Egypt a "gift of the Nile," he might just as well have called it the gift of Ethiopia. However, as will be discussed in Chapter 3, the traditional outlook on the "benefits" from these erosional sediments has been drastically altered following the construction of Egypt's High Dam. It is enlightening to note that erosion has always provided massive quantities of sediment, even under ancient (undisturbed) conditions when the vast majority of the plateau was in forest. Although a quantitative assessment of recent changes in the magnitude of erosion is not possible, suffice it to say that significant stands of timber now cover



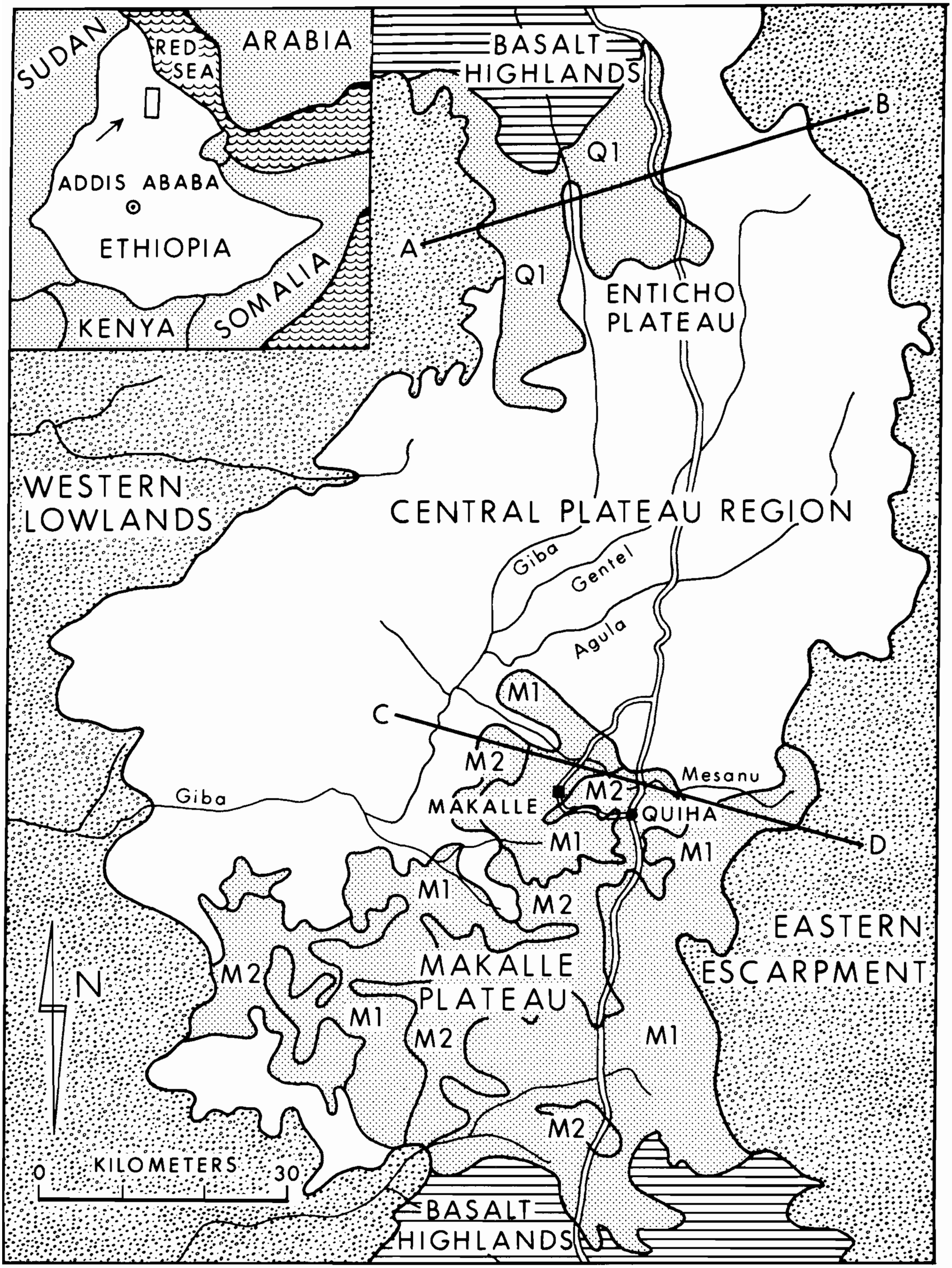
Map 5. Distribution of erosion and relationship to stock routes in the Kisongo catchment, central Tanzania. The areas of dendritic gullies bear little relation to stock routes, while linear gullies are generally close to the north-south stock routes. (After Murray-Rust 1972)

Table 10. Altitudinal zones of rainfall, land use, and soil erosion in the Morogoro River catchment, Tanzania

Land use zone	Altitude range (m)	Annual rainfall (mm)	Slope gradients	Farming	Intensity of erosion (estimated)	Types of erosion
Montane forest reserve	2100 1500	>2400	60° 30°	None	Slight	Few landslides; some splash and sheet erosion
Mountain farming	1500 900	2400 1500	42° 20°	Maize crop in January Goat grazing	Severe	Episodic landslides; sheet erosion; no gullying
Foothill farming	900 550	1500 900	35° 5°	Maize crop in April/May Goat grazing	Severe	Episodic landslides; sheet erosion; no gullying

Source: After Rapp, Axelsson, et al. 1972.

less than 4 percent of the country. The tempo of forest destruction has quickened since mid-century, and by the early sixties natural woodlands were disappearing at a rate of 1000 km² (100,000 ha) per year (Eckholm 1976). Quoting an unpublished paper by Ware-Austin (1970), Eckholm indicated that the extent of soil erosion in many parts of Ethiopia is so vivid that it will leave a lasting impression of desolation and impending disaster on even the casual visitor. He cited Brown (1971) in describing forest destruction and serious erosion, first in the North and then in the Central Highlands where the most obvious result was silt-choked rivers. A case study of the Gamu Highlands in southern Ethiopia led Jackson et al. (1968) as cited by Eckholm (1976) to conclude that the traditionally conservation-wise Chento people, who formerly kept their steep, erosion-susceptible land for grazing and protected their other cropland through fertilizer management and terracing, are now yielding to population pressures. They are plowing up grazing land, thus "violating their own land management rules" and (predictably) experiencing cyclic degeneration of their arable lands. In a recent paper, Virgo and Munro (1978) made an assessment of current erosional features and soil loss rates for the 6000 km² Central Plateau region in the North (Map 6). Using measurements of suspended sediment load for two catchments during the 1975 rainy season, they detected removal rates of 16.8 and 33.0 Tm/ha/yr. Recognizing the potential errors of using data records for only one year, they used the respective areas of the catchments (150 km² and 14 km²) in combination with Figure 5, to suggest that the above rates may reflect actual soil losses of 152.7 and 165 Tm/ha/yr. These compare favorably with losses of several hundred tonnes/ha/yr predicted for the three prevailing landform units in the plateau by the universal soil loss equation (Wischmeier and Smith 1978). Sample observations within these units revealed that nearly half the area is severely or very severely affected by erosion. Virgo and Munro (1978) also cited McDougall et al. (1975), who estimated overall current sediment loss rates of 2-4 Tm/ha/yr. This reflected a significant acceleration (due to seventy years of deforestation) beyond the Quaternary geological rate of 0.25 Tm/ha/yr over the upper catchments of the Blue Nile and Atbara (Tecezze) river systems. Comparison of aerial photographs from 1965 and 1974 indicated that gully erosion, a form which was scarcely noted as late as 1943, prevails in the Vertisol-dominated Makalle region. Such gully formations, enhanced by tunnelling, are encroaching at the rate of 5-10 m/yr and may be linked to the progressive destruction of calcium carbonate barriers (tufas) that had formed at stream outlets under original, stable equilibrium conditions. In contrast, stream outlets in the Enticho



Map 6. Location map for erosion studies in Ethiopia by Virgo and Munro (1978).

Plateau are controlled by acid metavolcanic and igneous rocks that are resistant to down-cutting and subsequent gullying.

Large parts of Tanzania and Nigeria are infested with tsetse fly (*Glossina* spp.). According to R. Fiennes (cited by Maher 1972) in 1964 60 percent of Tanganyika—as it was then known—was controlled by the fly. Although it has been said frequently that the tsetse fly has protected large areas from erosion, by preventing the ingress of cultivators and their domestic animals and so preserving the natural cover, H. E. Hornby (also cited by Maher 1972) disagreed. He suggested that such protection of the land by unmolested bush cover had been at the expense of overcrowding people and cattle on the outskirts of the tsetse belt; that the absence of surface water has been a more important factor in safeguarding the vegetative cover; and that if the flies had contributed to the conservation of the bush over large areas, so preventing erosion, it had been at the expense of death to people and animals (through sleeping sickness and trypanosomiasis of cattle, respectively—the diseases carried by the fly).

Western Africa

A recent account of soil erosion and farming systems in West Africa was given by Okigbo (1977). Lal (1976*d*) and Roose (1977*b*) have given detailed presentations of the results of many years of erosion studies in the Alfisols (Ferrallitique) and Oxisols (Ferruginous) soils of the region. These and other studies, as well as Fournier's map of erosion hazard (Map 3), show that most of this tropical region is very susceptible to rainfall erosion. However, such statements have not been supported by detailed site surveys of the extent of erosion. Roose (1977*c*) cited other workers in reporting that erosion rates for small plots on research stations in Senegal, Ivory Coast, Upper Volta, and Benin (Dahomey) ranged (depending on steepness of slope and soil type) from 0.01 to 0.07, 0.1 to 90, and 3 to 570 Tm/ha/yr under natural, cropped, and bare conditions, respectively. Sheet and rill erosion are considered the dominant forms of erosion and are responsible for most soil losses, particularly in unprotected soils. Obeng (1973) indicated that widespread accelerated soil erosion under cereal crop cultivation in Ghana was enhanced by vegetation clearing, burning, and indiscriminate use of unsuitable mechanical implements prior to planting. In addition, many cases of disastrous gully erosion have been documented in western Africa.

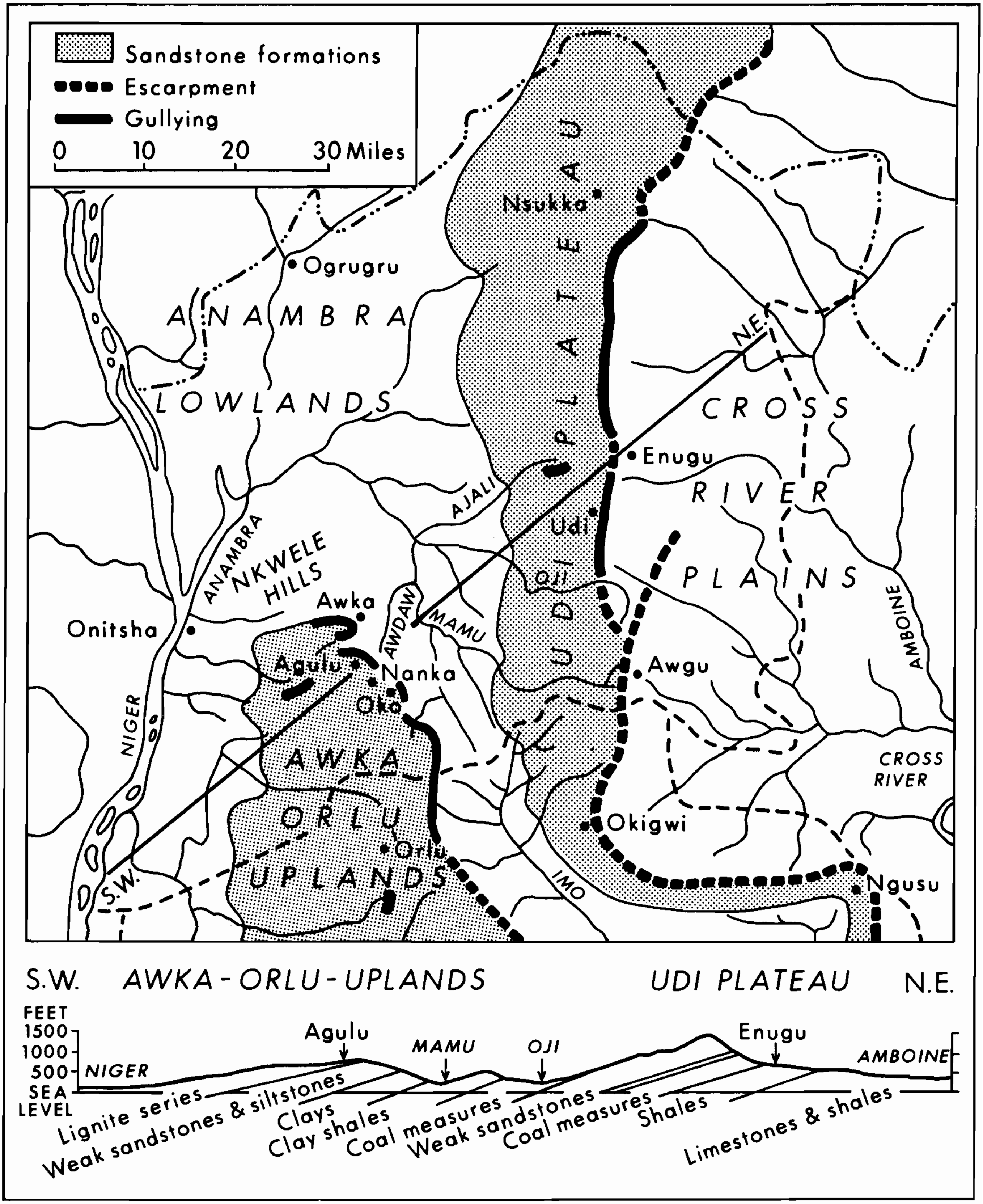
In Nigeria, Okigbo (1977) referred to the vast and spectacular gullies that now characterize the Nanka, Agulu, Oko, and Enugu areas of Anambra State, the Shendam and western Pankshin areas of Plateau State, and parts of the East Central State. Erosion damage to the latter was estimated at 13 million Tm/yr; the gullies extend to over 120 m deep and up to 2 km wide. Onyeagocha (1975) indicated that over 25,000 ha of land are badly eroded and gullied in many parts of the former Eastern Nigeria. They cannot be farmed, nor can they maintain any form of vegetation. Many areas bordering these badly eroded lands are fast losing their existing cover and becoming equally bare, with threatened gully formations. Floyd (1965) in an older appraisal of the same area (Map 7) wrote:

> The eastern region of Nigeria has one unfortunate claim to fame which might better be left unpublicized, except that it relates to a problem of monumental proportions and one of great interest and concern to geographers, pedologists, agriculturists, conservationists, as well as other scientists the world over. Dramatic gully erosion is most evident in the plateau and escarpment zone particularly along the scarp of the Awka-Orlu uplands and the Nsukka-Okigwi escarpment in the East. Less pronounced, though equally insidious, sheet and gully erosion is widespread across the region however, extending from the plateaus in the Northwest as far south as the coastal plains, the Ikot Ekpene-Itu-Uyo triangle and eastward to the Cross River basin. Soil deterioration and degradation in terms of the progressive loss of nutrients and breakdown of structure, is well-nigh universal, due largely to overfarming and primitive, destructive methods of cultivation.

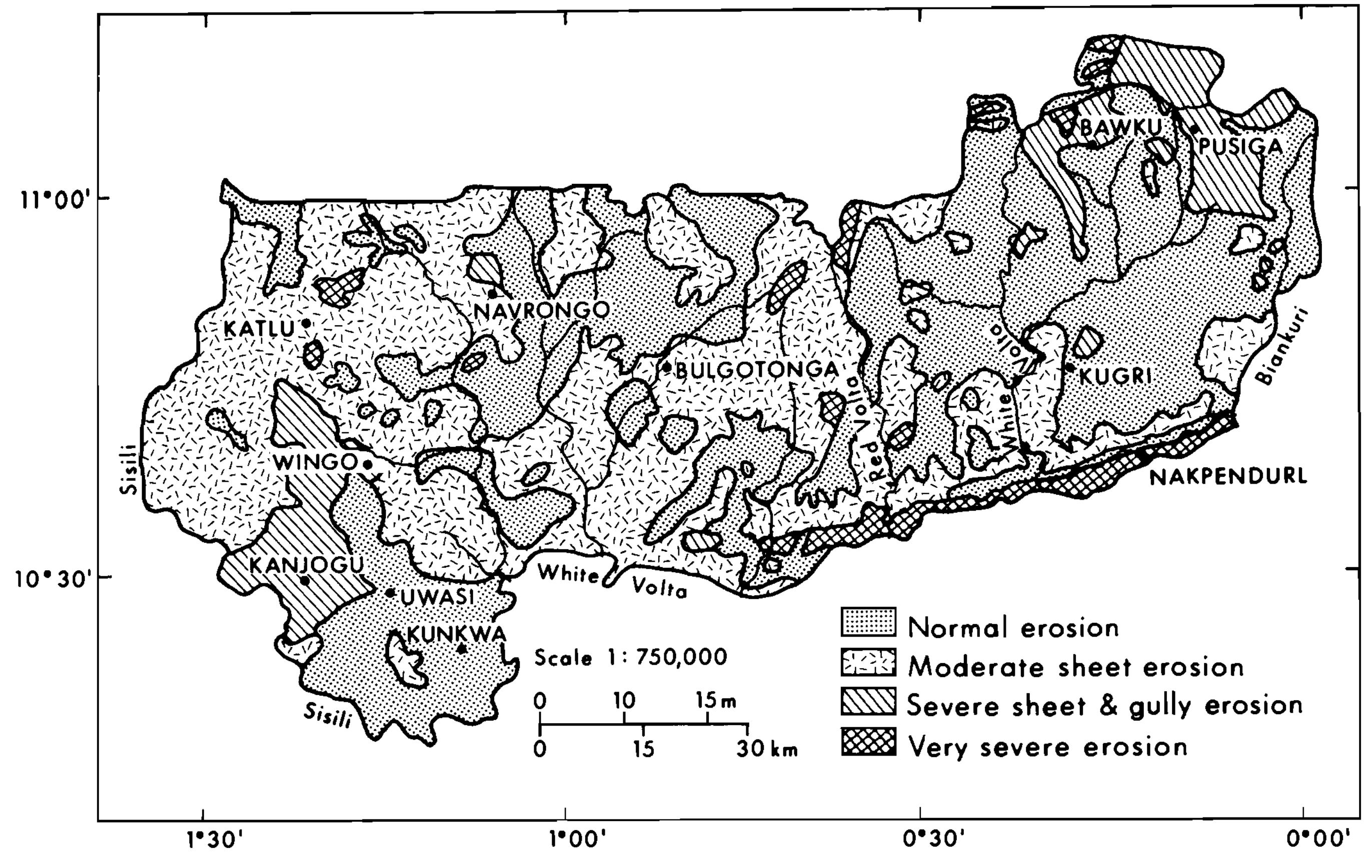
Floyd showed several plates displaying the awesome nature of the gullying problem in the area.

In the Navrongo-Bawku area of northeastern Ghana, which covers over 9000 km^2 (Map 8) and has a population of about 500,000, soil erosion has been described in a survey by Adu (1972). He estimated that approximately 40 percent of the area has been eroded to a depth of 0.9 m resulting in the loss of practically all plant nutrients. A further 8 percent of the area has been so severely eroded that a complete loss of both the A and B soil horizons has occurred.

In Senegal, Charreau (1968) indicated that the failure of land developers to establish conservation



Map 7. Geology and structure of the Udi Plateau and the Awka-Orlu Upland of eastern Nigeria. (After Floyd 1965)



Map 8. Location, extent, and severity of soil erosion in the Navrongo-Bawku area, northern Ghana. (After Adu 1972)

requirements for newly cleared lands resulted in massive erosion problems and subsequent losses of investment. He added:

> The phenomena of erosion by water are sometimes spectacular, especially in the southern region, where rainfall is highest. One recalls in particular the unfortunate experience of the members of the former CGOT (La Compagnie Generale des Oleagineux Tropicaux) in the fifties and their amazement when they discovered year after year the implacable progress of erosion on newly cleared land, even though the slopes were very slight, with a maximum of 3%. Towards 1952, the effects were so vast that radical measures had to be taken. In particular, it was necessary to give up any hope of cultivating several hundred hectares, thus losing the vast sums devoted to clearing them—the brush had to be allowed to reconquer the land.

A recent study by Heusch (1981) showed that water, not wind, was the prime cause of erosion in the Ader Dutchi Massif region of Niger, an arid area subject to a Sahelian climate. Erosion from one watershed, 117 km^2 in area, was estimated by reservoir sediment deposit surveys to average 40 Tm/ha/yr during a period that saw below average rainfall. Heusch estimated this rate to be about twenty-five times greater than normal geological erosion. Small plot studies near the watershed averaged only 8 Tm/ha annual soil loss, indicating that gully and stream bank erosion contributed the major share of material eroded from the watershed. Soil mapping in the surrounding 1000 km^2 area showed that twenty-five percent was clearly subject to sheet erosion and that rates of gully erosion can exceed 500 m/km^2.

Rainfall Erosion in Tropical Asia

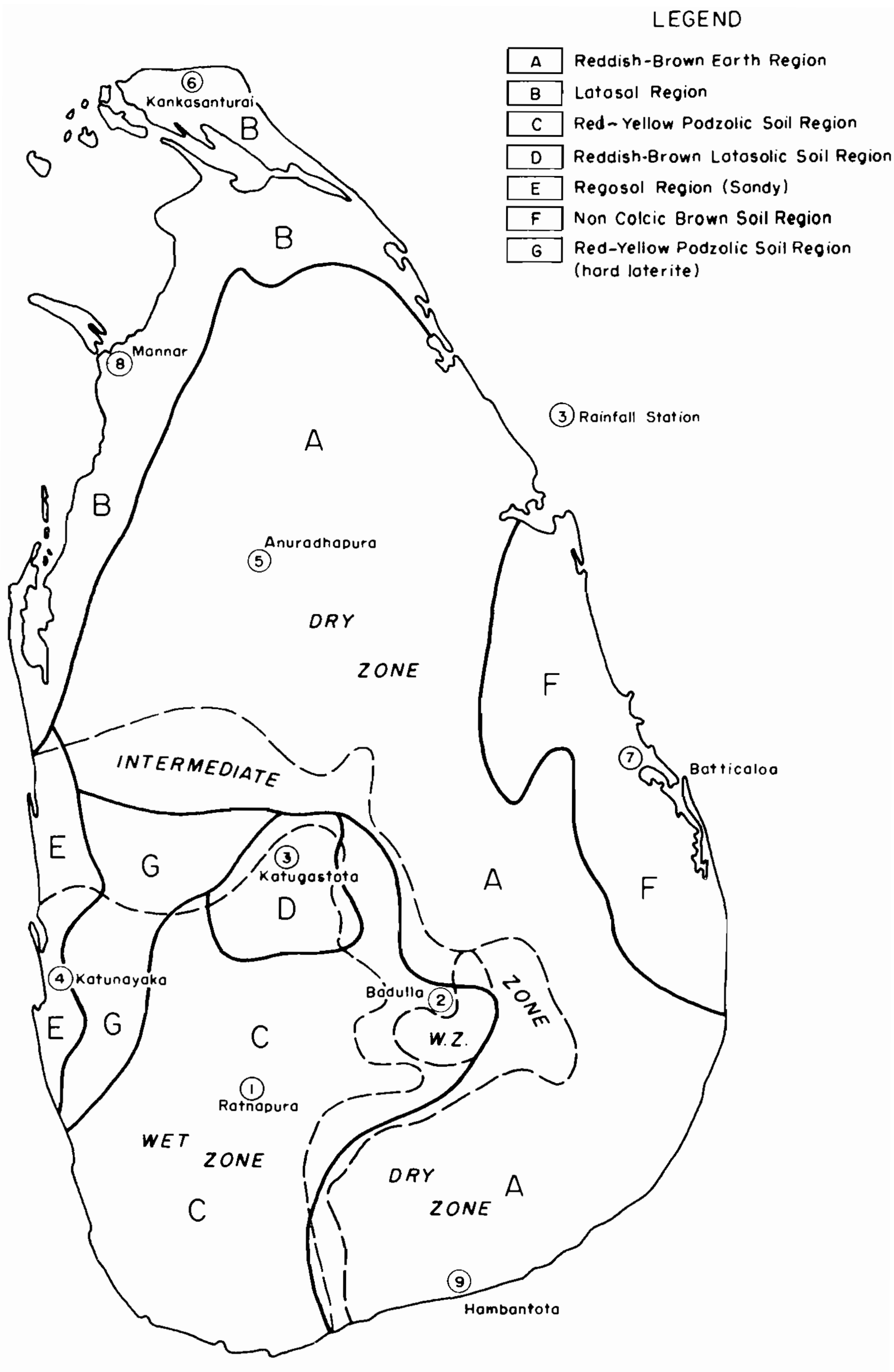
Asia has the greatest land area of all continents, but many of its regions have a disproportionate population density. For example the population density of India is 182 persons/km^2; the Philippines, 142 (United Nations 1977); Java and Madura, 576 (Soemarwoto 1974) and Java itself, 620 (Thijsse 1976). Comparing these data with the density in the United States of 23 persons/km^2 (United Nations 1977), and the ever-increasing magnitudes of population densities elsewhere, the urgent and constantly expanding need for food and fiber in Asia becomes evident. Yet it may be recalled from Table 2 that this continent has the dubious distinction of possessing the highest rate of river sediment loss (1.66 Tm/ha/yr) of all the continents. Still higher—indeed excessive—are the estimated losses ranging from 21 to 555 Tm/ha/yr for the selected Asian river basins shown in Table 3. Crude as this index of soil erosion may be, Asia must be considered subject to widespread soil losses. The associated decline in land productivity (chap. 3) enhances the need to bring more and more forestlands under cultivation. The excessively high sediment losses are well explained by such continued practices as widespread clearing (since World War II) of the Dipterocarp forests for lumber or cultivation in Indochina, Indonesia, Malaysia, the Philippines, and Thailand (Meijer 1973). It has been estimated that during the Vietnamese War nearly 2 million ha of forest was destroyed in Vietnam. In India, the Ganges, Kosi, and Damodar rivers carry perhaps the highest sediment load of any Asian rivers surveyed, indicating the seriously high erosional losses from their drainage basins. Estimates of soil losses carried as sediment in the Red, Irrawaddy, Mekong, and Chao Phraya rivers all exceed the "desirable" tolerance limit of 11 Tm/ha/yr. Clearly, soil erosion in tropical (i.e., South and Southeast) Asia is of serious proportion. The following is a breakdown of available information from these two regions.

Extent of Rainfall Erosion in South Asia

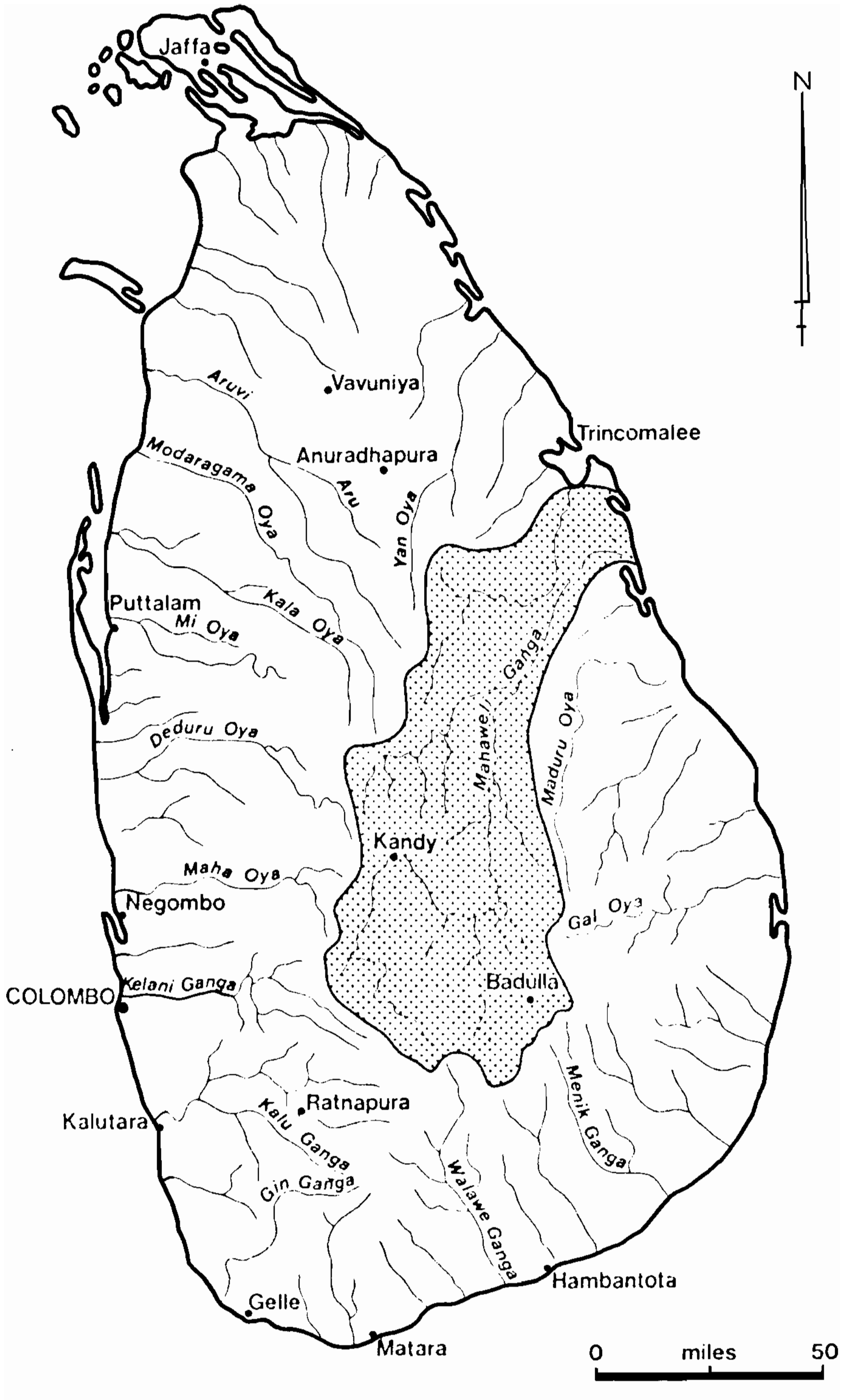
Recent accounts of erosion problems in this region have been provided by Panabokke (1977) and Lal (1977*c*). However, neither these authors nor other available publications provide quantitative estimates of existing or potential erosion.

In Sri Lanka, Burns (1947) indicated that nearly 25 million tonnes of soil are lost annually as sheet wash due to rainfall erosion, and that landslides contribute to the devastation caused by floods. Lal (1977*c*) cited several early publications that documented erosion problems on the island. Most impressive is the massive clearing of natural forests (nearly 200,000 ha) in the central highlands since the introduction of tea and coffee as agricultural crops early in the last century. Burning of grasslands also contributes to soil erosion, but to a lesser extent than forest clearing. Tea plantations, common up to altitudes of 2000 m and on slopes as steep as 60 percent, represent a significant erosion hazard. On a slope of 30 percent, Holland and Joachim (1933, cited by Lal 1977*c*) measured annual soil losses of 39.9, 34.1, and 20.4 Tm/ha in tea alone, and in tea with two different cover crops. Similarly, Hasselo and Sikurajapathy (1965, cited by Lal 1977*c*) measured soil losses from bare plots on tea plantations at 52.6 Tm/ha in a two-and-a-half-month rainy period. Mulched plots lost 20–22 Tm/ha during the same period. Fortunately, erosion hazards for many tea and rubber plantations on the steep terrain are somewhat reduced by good management and the abundance of soils with low susceptibility to erosion, namely Ultisols. However, serious erosion does occur on these slopes in marginal tea and rubber stands that provide little protection to the soil. Erosion hazards on the island are quite variable due to the large spatial variability in topography, vegetation, rainfall, and soil distribution (Map 9). Erosion hazards are more severe on Alfisols than on Ultisols but less severe on Oxisols (Panabokke 1977). The severity of erosion on Alfisols is due to high soil erodibility, low infiltration rates, uncontrolled population settlement patterns, and lack of adequate (protective) cropping sequences. Lower erosion on Ultisols is due to limited population density, high infiltration rates, and relatively flat terrain.

According to Hudson (1978), the recent evolvement of "a crop diversification program, which recommends the cultivation of nontraditional plantation crops on sloping lands, poses a new soil erosion hazard." He reported preliminary soil loss results of up to 250 Tm/ha during a tea replanting period of 4 years in such regions. As a result of his recommendation, some of the parameters required for quantitative assessment and prediction of the extent and causes of erosion are being studied at various locations on Sri Lanka. Erosion and watershed deterioration are of specific concern in the upper catchments of the Mahaweli Ganga basin (10,370 km^2, Map 10) which is characterized in places by as much as 5000 mm of rainfall per year (Chambers 1977). In 1968, the FAO (according to Chambers 1977) prepared a master plan for its development, calling for the irrigation of 400,000 ha and the generation of hydroelectric power. Present land use in that steep and mountainous region consists of only 30 percent natural forest, grassland, and forest plantations. The



Map 9. Agroclimatic zones and major soil regions in Sri Lanka. (After Joshua 1977)



Map 10. Sri Lanka, showing the Mahaweli Ganga basin. (After Chambers 1977)

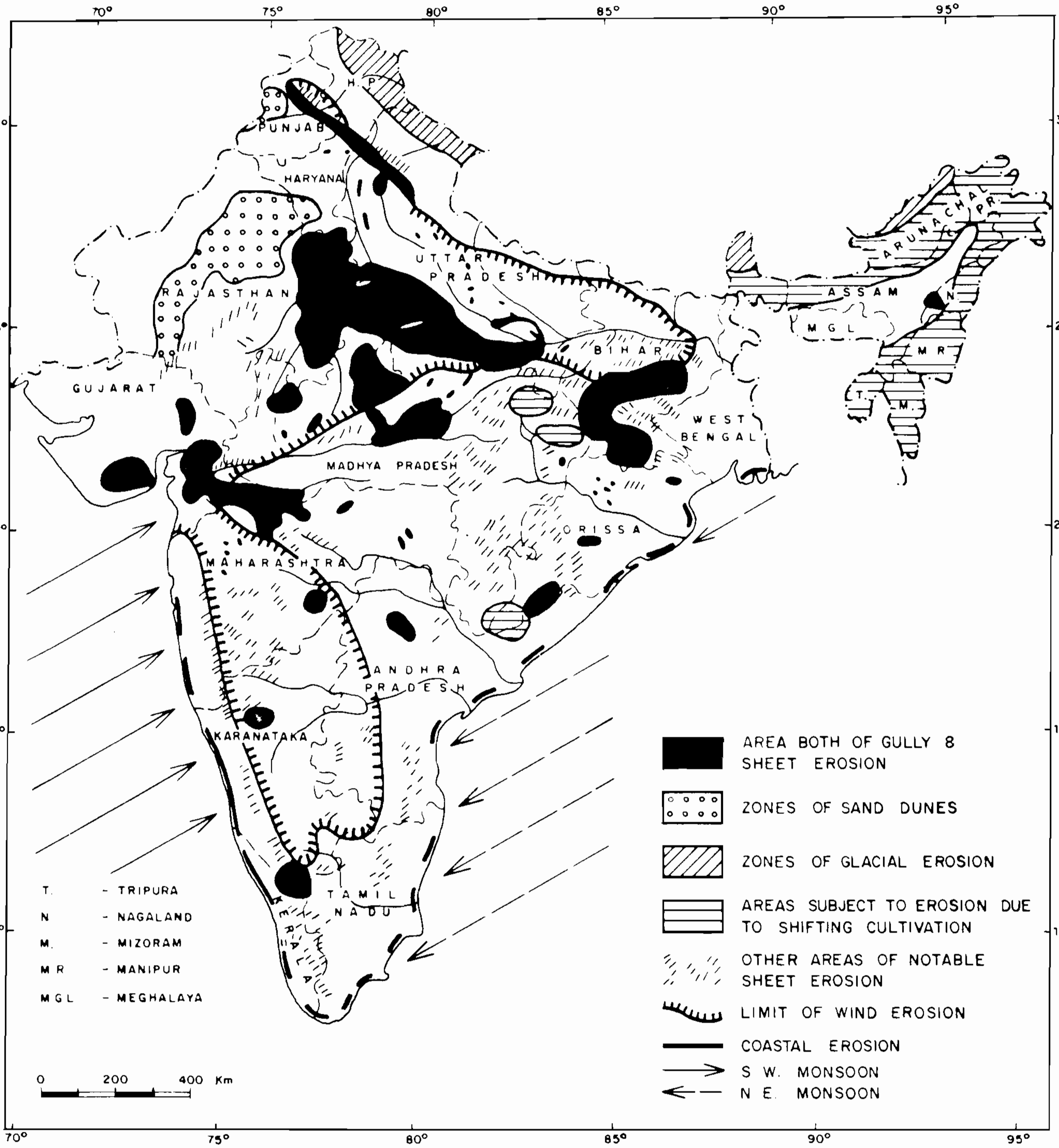
remainder is under some form of agricultural use, mostly tea, homestead gardens, vegetable gardens and paddy, with seasonal cropping and shifting cultivation becoming increasingly important. Some lands that have been opened for seasonal cropping and shifting cultivation are of such erosion hazard that they "cannot be stabilized under any agricultural system and should be allowed to revert back to natural vegetation or be used for plantation forestry where this can be shown to be economical" (Chambers 1977).

In India, awareness of soil erosion problems is evident from the large volume of erosion literature. Together with many general articles are a few quantitative studies. In 1961, the Planning Commission estimated that nearly one fourth (81 million ha) of the land in India was suffering soil erosion (Ahmad 1973). Das (1977) puts that figure at 150 million ha by adding the area affected by wind erosion, a very serious factor in the Rajasthan Desert and elsewhere (Patnaik 1975; Table 11; Map 11). Tropical and subtropical areas subject to erosion, and thus in need of conservation measures, include the Central Indian Plateau, the Deccan Plateau (excluding the forested belt), the Chota Nagpur Plateau, and the areas of red soils in West Bengal. The combined area in these regions is about 58 million ha, not including the extensive and severe gully erosion found in the Chambal region, in Gujarat, and on the Ganges Plains. It may be recalled that rivers in this subcontinent possess perhaps the highest erosional sediment loads of any in the world (Table 3). An overall estimate of the amount of soil lost by water erosion in India is 250 Tm/ha/yr (ICAR 1969, cited by Lal and Banerji 1974). This is a staggering figure which exceeds twenty times the conventionally tolerable limit for soil loss (chap. 1). According to Eckholm (1976), a senior Indian agriculturist has stated that he believes the country is approaching the point of no return with its resource base; if momentum is not soon generated in reforestation and soil conservation programs, India will find itself with a billion people to support and a countryside that is little more than a moonscape. Approximately 47 percent of the land is used for agricultural production and much of it is subject to high erosional hazard. According to a recent report (CSWCRTI 1977) the erosion problems in India began to accelerate after the eleventh century, with forest exploitation and destruction by the Moghals, and the later development of exploitive agriculture in the nineteenth century. At present there is very little land free from erosion hazard. Accelerated erosion is evident from ravines on the banks of the Chambal, Jamuna, and Mahi rivers and their tributaries causing annual losses of 2.3 million ha. The denudation of forests and vegetation in the Siwaliks and the Himalayas has resulted in flash floods, destroyed agricultural lands, silted up reservoirs, disrupted communications and produced losses of life and property. In the same report, the institute stated that if erosion is permitted to continue at the present rate, the task of the future will be soil reclamation rather than conservation. The seriousness of the problem has inspired the establishment of a chain of soil conservation research, demonstration, and training centers during the first and second Five Year Plans of India (1954–1962). Of these, the institute originally established to serve the northwestern Himalayas region is now the Central Soil and Water Conservation Research and Training Institute (at Dehra Dun). The concern of the authorities for the serious erosion problems in the country is further illustrated by the declared national goal of "revegetation of denuded

Table 11. Estimated extent and types of erosion in India

Category	Area (Million ha)
Total geographical area	328
Total area subject to serious water and wind erosion	150
Area at critical stage of deterioration due to erosion	69
Area subject to wind erosion	32
Area affected by gullies and ravines (approximate)	4
Area affected by shifting cultivation (approximate)	3
Area under rainfed farming (non paddy)	70

Source: After Das 1977.



Map 11. Extent and types of erosion in India. (After Das 1977)

lands by expanding the current 23 percent of the land occupied by forest to 33 percent." The International Crops Research Institute for the Semiarid Tropics (ICRISAT) devotes much of its Farming Systems Program to developing effective soil and water conservation practices in central India.

Although not strictly within the tropical zone, Nepal (latitude 27-30° N) will be included briefly in this discussion as an illustration of extremely visible degradation of a mountainous terrain within the Himalayan arc. Similar problems plague large areas within India, in such states as Himachal Pradesh, Uttar Pradesh, Assam, Jammu, and Kashmir. The impact of extensive erosion has been documented not only in Nepal and northern India but also on the lower portions of the Indian subcontinent. As Eckholm (1976) stated for Nepal,

> Population growth in the context of a traditional agrarian technology is forcing farmers onto ever steeper slopes, slopes unfit for sustained farming even with the astonishingly elaborate terracing practiced there. Meanwhile, villagers must roam farther and farther from their homes to gather fodder and firewood, thus surrounding most villages with a widening circle of denuded hillsides. Ground-holding trees are disappearing fast among the geologically young, jagged foothills of the Himalayas, which are characterized by soils among the most easily erodible anywhere. Landslides that destroy lives, homes and crops occur more and more frequently throughout the Nepalese hills.

Eckholm also expressed the opinion that "Topsoil washing down into India and Bangladesh is now Nepal's most precious export," and that as a result of declining soil productivity, "as much as 38 percent of the total land area consists of abandoned fields," which are naturally more prone to erosion during monsoonal downpours. To avoid impending disaster, the author further cautioned that settlement of the now relatively unexploited plains of the Terai must be controlled to eliminate illegal clearing of forestlands by migrants from the hills—at a rate estimated to have exceeded 230,000 ha during the decade from 1964 to 1974. Although quantitative data on the exact extent and dominant types of erosion-affected areas are not available, this information illustrates the general gravity of the situation in Nepal.

Extent of Rainfall Erosion in Southeast Asia

It may be recalled from Table 3 that alarming sediment removal rates were monitored for the larger basins of the Chao Phraya (Thailand) and Irrawaddy (Burma) (21 and 139 Tm/ha/yr, respectively). Table 12 provides a more detailed breakdown of sediment transport by rivers in that region. The seriousness of the problem is illustrated by the fact that at least the first eleven river basins listed are subject to severe rainfall erosion. Using a sediment delivery ratio of 0.05, soil losses in the field may be estimated to range from 20 to 750 Tm/ha/yr. This whole region is seriously afflicted by the proliferation of deleterious grasses that often succeed cleared forests during shifting cultivation. Old cogon *(Imperata cylindrica)* is the chief problem in this area. Ranchers in the Philippines burn vast areas of land at the peak of the dry season in an attempt to eliminate this unpalatable grass and to provide young growth for forage. When the rainy season commences, surface cover is scanty, providing little protection against erosion. Furthermore, burning actually favors the establishment of *Imperata cylindrica* over other forage grasses.

In Singapore (Keng and Koon 1972), the current land-use pattern is characterized by only 6.4 percent of the area remaining in water catchment and forest reserves. Extreme changes have occurred in the hydrological regime, causing the island to be extremely susceptible to flooding. Sien and Koon (1971) described one major storm that produced nearly 330 mm of rainfall and caused widespread damage to the island.

Peninsular Malaysia was considered by Morgan (1974) to have moderate erosion hazard as judged by the concept of drainage density (i.e. the length of streams per unit area). This situation exists despite the fact that 55 percent of the total area is still in forestland. Sabah and Sarawak still have 86 and 76 percent respectively of their total areas in forest, precluding serious erosion problems except in extensively logged areas. Substantial areas of land are still "available" for agriculture, both in Peninsular Malaysia and Sabah and Sarawak (Gopinathan 1977). Studies of soil erosion which have hitherto been virtually ignored (Chim 1974), must now be emphasized to avoid uncontrolled replacement of forest by cultivated crops. The seriousness of this hazard in Malaysia is further illustrated by the fact that steep slopes (>20%) comprise nearly 40 percent of the land. Malaysia suffered serious sedimentation prob-

Table 12. Suspended sediment loads of some Southeast Asian rivers, listed in decreasing order

River	Location	Drainage area (km^2)	Suspended load (Tm/ha/yr)
Tjatjaban	Java	79	37.5
Tjiloetoeng	Java	620	20.3
Dry-zone rivers	Burma	92,500	7.60
Chindwin	Burma	114,500	5.21
Irrawaddy	Prome, Burma	367,000	4.64
Rambut	Java	45	3.00
Mekong	Vientiane, Laos	299,000	2.46
Mekong	Stung Treng, Kampuchea	534,000	1.95
Bertam	Cameron Highlands, Malaysia	73	1.55
Irrawaddy	Mandalay, Burma	160,000	1.33
Gombak	Kuala Lumpur, Malaysia	140	1.01
Selanbor	Battambang, Kampuchea	3,230	0.350
Telom	Cameron Highlands, Malaysia	77	0.317
Kompong Lar	Thnot Chum, Kampuchea	420	0.297
Sen	Kompong Thom, Kampuchea	13,670	0.248
Pursat	Pursat, Kampuchea	4,480	0.222
Babaur	Babaur, Kampuchea	870	0.170
Staung	Kompong Chen, Kampuchea	1,895	0.164
Krakor	Krakor, Kampuchea	138	0.12

Source: After Douglas 1968, cited by Lal 1977c, modified.

lems early in this century from indiscriminate logging, tin mining, and bad cultural practices. Sediment buried the township of Kuala Kubu under several feet of silt (Daniel and Kulasingam 1974). These authors documented that, as a result of large amounts of topsoil having been lost because of undesirable agricultural practices (with rubber, gambier, pepper, and pineapple cultivation), the banks of the Kelantan, Perak, and Pahang rivers have been raised up to 20 feet (6m) above the surrounding land by sediment deposition during floods. In one early appraisal of soil and water conservation in Malaysia, Speer (1963) noted that "numerous areas from which forest and jungle have been cleared were not capable of producing any other crop safely or economically. They may be stoney, too steep, of low fertility, or highly erodible soils, or a combination of these characteristics." He recommended that such areas be returned to forest. Speer also noted that plantings of pepper, tea, vegetables, tobacco, cassava, bananas, pineapples, rubber, and oil palm were all associated with serious erosion problems. He recommended that within these areas, lands unsuitable for cultivation should be reforested, and that crop production on the suitable lands be stabilized by contouring and bench (or broadbase) terraces to reduce both soil and water losses. He indicated that special emphasis should be given to the hilly regions within the Cameron Highlands (where erosion is enhanced by construction activities to serve the fast expanding tourist industry), Bukitinggi, Kulai, and lands between Kuala Kangsar and Grik. It was the impression of El-Swaify, following a recent site visit, that the large estates of rubber, oil palm, and coconuts are generally well managed for erosion control, using a combination of terracing and early plantings of protective ground covers on steep slopes. Erosion hazards are generally high if tree and ground cover plantings are not completed before the monsoon season, or on small plantations where soil protection either is not prescribed or is ignored. Serious erosion on denuded steep lands is illustrated by estimated soil losses of 392 and 598 Tm/ha from bare forest plots on 32° and 35° slopes (Chim 1974; with the assumption that bulk density of soil removed from rills = 1g/cc). In the Cameron Highlands, Shallow (1956, cited by Daniel and Kulasingam 1974) measured much higher rates of soil loss (4.9 and 7.3 Tm/ha/yr under vegetables and tea), than the 0.24 Tm/ha/yr measured under natural jungle vegetation. Fortunately the 1960 Land Conservation Act designates lands with slopes not exceeding 18.5 percent as the legal limit for cultivation development. To insure the benefits of the Act, Speer (1963) recommended that a strong program be developed to stop illegal occupation of land and to correct misuses on currently illegally occupied land. It is important at this point to note the almost complete lack of information on the extent of soil erosion in nonpeninsular Malaysia. However, it is safe to assume that both parts of the country are currently in a strong position to prevent serious deterioration of the land resource base, much of which is still undeveloped.

Thailand is in a very similar position. As recently as 1940, the country did not have many serious problems with erosion. Pendleton (1940) reported that most of the erosion noted in the central plain was due to channel scouring in the main rivers. In Phuket Island, and elsewhere in southern Thailand, serious but localized erosion existed. In one of the few recently reported quantitative studies, test plots reporting cleanly weeded coffee in Tarnto Settlement produced soil losses of 25–30 Tm/ha/yr on 12° slopes (Virgo and Holmes 1977). This area is representative of a 220,000 hectare tract in southern Thailand, 40 percent of which is natural forest; it is estimated that 1500 hectares of that forest are destroyed annually. Many incidences of tunnel erosion are seen in the northeast where saline and sodic conditions lead to differential weaknesses in soil structure and cause localized soil dispersion and removal by runoff. However, the most serious erosion, both existing and potential, occurs in the forest watersheds of the northern highlands which form the physiographic headwaters of the principal rivers and produce 70 percent of the country's timber. Rainfall totals and patterns are relatively uniform throughout the central plateau and the northern highlands, with most precipitation falling between May and October in monsoonal storms (Fig. 9). However, the northern highlands are characterized by topographic conditions that are more conducive to erosion when forest vegetation is cleared. Teak logging, shifting cultivation (swiddening) of essential crops as well as opium, and tin mining have all caused serious erosion in recent years. Inadequate conservation practices are frequent in the steep lands of the northern forest reserves (with slopes ranging up to 65%) under shifting cultivation. A recent review of farming in this region was presented by Kunstadter et al. (1978). To date, cleared lands have amounted to a total of 2.4 million ha out of a total of nearly 10 million ha, and clearing continues at the rate of more than 50,000 ha/yr. Crop selection and management practices often are not conservation oriented, as illustrated by harmful soil disturbances associated with the harvest of root crops on susceptible

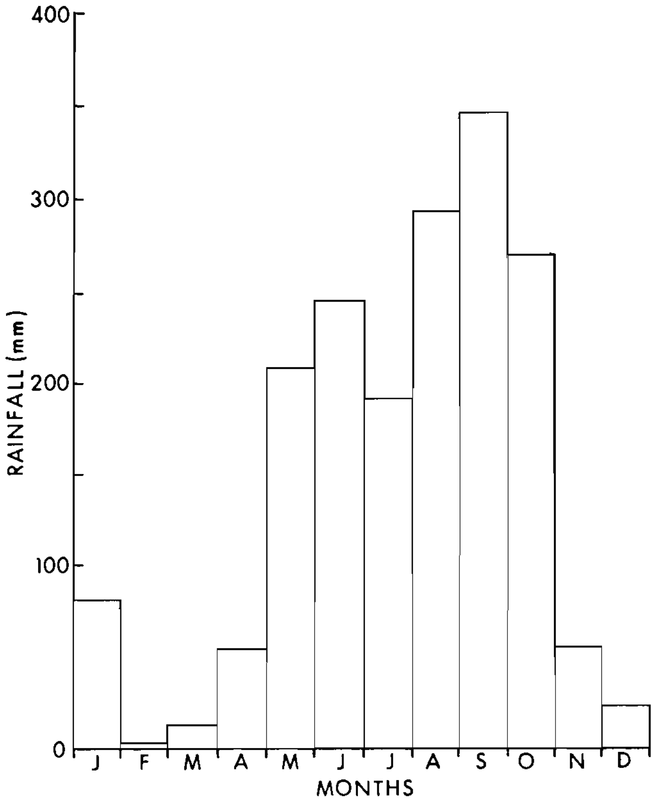


Figure 9. Annual rainfall pattern for Thailand's northern highlands during the period 1975–1977. (Sheng, T. C. 1978, informal communication)

soils and slopes during the rainy reason. Uncontrolled fires often result from the burning of newly cleared areas and contribute to the degradation of the forest watersheds. However, despite the widespread use of shifting cultivation in northern Thailand, overall damage caused by soil erosion is less noticeable than in, for example, India. This is due to less population pressure, deeper soils that are better able to provide vegetative regrowth, and a mildly aggressive climate. Serious research efforts to stabilize agricultural development have begun in the north, both within the Ma Sae Integrated Watershed and Forest Land Use Project (FAO-UNDP-Royal Forestry Department) and the Thai-Australia Land Development Project (Land Development Department–Australian Assistance Program). While both have the objective of developing and stabilizing lands under rainfed agriculture that are now being farmed on an intensive slash and burn (swidden) system of shifting cultivation, the first project deals with steep forestlands, and the second with lands that are in secondary forest and generally have "gentle" slopes of less than 10 percent but are still subject to high erosion hazards. The Soil and Water

Conservation and Management Division of the Land Development Department maintains 22 land development centers throughout the country, for the primary purpose of developing appropriate methods for sustained agricultural production. However, little quantitative information is available, as much of the data analysis and synthesis still remains to be done.

For Indonesia, little quantitative information on the extent of soil erosion has been documented. However, rainfall and topographic patterns, combine to give the islands perhaps the highest rainfall erosion hazards in Southeast Asia. Most of the erosion literature is from Java and is based on sediment loads in rivers. Selected data given in Table 12 show three rivers whose sediment loads rank extremely high among the rivers of Southeast Asia. Additional alarming annual sediment loads include 3.1 million tonnes for the Citarum River at Warungjeruk in west Java and 8.6 million tonnes during the 5-month rainy season of 1971–72 for the Solo River in central Java. Partosedono (1974) has described the extent of erosion for the 3322 km^2 catchment area of the Cimanuk River. He estimated the depth of soil lost annually to erosion at 5.2 mm, compared to 0.7 mm, which is the overall average for the land surface of the globe; and the problem seems to be accelerating. The yearly erosion of the Citulung basin (west Java) was 0.9 mm during 1911–12; 1.9 mm during 1934–35; and is currently estimated at 5 mm (Soemarwoto 1974). This author also estimated that a staggering 17 cm of soil was lost from 10,500 ha of steep lands in the Upper Solo watershed during the 5-month rainy season of 1971–72. Another study south of Bandoeng at Tjiwidei in Java, contrasted soil losses from terraced and unterraced plots. After clearing virgin forest, sediment loss was 5.27 Tm/ha/yr on the unterraced site and 1.35 Tm/ha/yr on the terraced site. Soil losses were greatly enhanced during the second year after clearing; sediment losses of 50.47 Tm/ha/yr and 24.68 Tm/ha/yr were measured for the unterraced and terraced plots, respectively (Shallow 1956, cited by Leigh and Low 1973).

The Philippines, with a total land area of 30 million ha, has nearly 11 million ha of cultivable land, three fourths of which are badly eroded (Miranda 1978; Bureau of Soils and PCARR 1977). Historically, it is acknowledged that by 1946 about 9 million ha or three fourths of the cultivated and open land had been subject to all forms of erosion (Table 13). Of these, the 4 million ha planted to upland seasonal crops were subject to severe erosion and the remaining 5 million ha to less severe forms. The high erosion hazards in the country are illustrated by the generally wet climate and steep topography. Most of the land receives more than 2,000 mm of rainfall annually (Map 12). At least 31 percent of the total land area is described as hilly, mountainous, rough, or rugged (nearly one million ha of agricultural lands have slopes of 8–15%), and subject to severe erosion during the rainy season. The rate of forest destruction for cultivation on hilly land has been estimated at 180,000 ha/yr, a figure that continually increases the area susceptible to erosion. At present the Philippines has 5.1 million ha of land in need of reforestation. Of these, 1.4 million ha in forest reserves have been proclaimed critical watersheds due to their vital importance for supplying irrigation and municipal water, generating hydroelectric power, producing fish, or combinations thereof. Indiscriminate logging for lumber, mining, and/or cultivation has also increased the extent of erosion in the major river basins. Miranda (1978) provided sediment yield figures of 44.60, 11.42, and 0.68 Tm/ha/yr for the basins of the Agno, Pampan, and Marbel rivers, respectively. He also gave an account of serious erosion problems in the basins of the Bicol, Agno, Magat, and the Pampanga rivers. In the 574,000 ha Agno River basin, 183,968 ha (32%) are undergoing severe erosion, with landslides common along road cuts and very steep slopes. Maps of lands licensed to timber companies show between 37 and 85 percent of the area as severely to very severely eroded (Table 14). With increased population pressure, vegetable gardening in the upper Agno basin has now expanded into the critical watershed areas, with severe soil erosion consequences. Similarly, slopes with steepness exceeding allowable limits for cultivation are being cultivated or grazed within the Magat River basin. Of the basin's total area of 414,300 ha, an estimated 216,000 ha are now subject to either severe or very severe erosion. Serrano and Suan (1976) cited Meceda (1948–49) as noting that erosion problems were accelerating even then. Data they provided for the extent of erosion in different regions were consistent with those given in Table 13. In addition they observed that gullies are forming on the steep hillsides of Mountain Province at the rate of 1 million m^3 of bed-load per km^2 of gully area per year (Gulcur 1965, cited by Serrano and Suan 1976). These two authors (and Tautscher 1974, whom they cited) indicated they believe that roads may be the

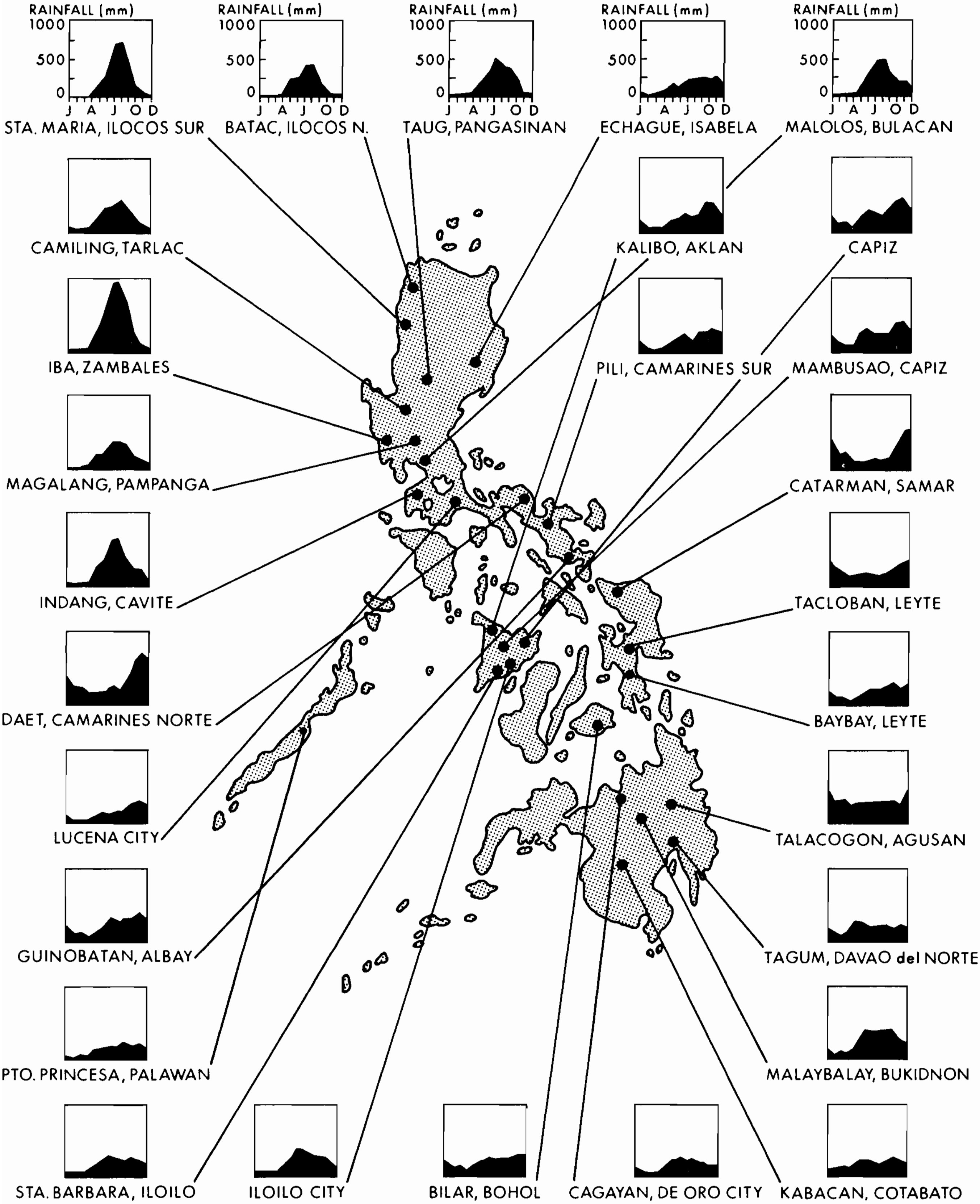
Table 13. Erosion extent in the Philippines

Provinces*	Land subject to erosion (ha)	(%)	Provinces	Land subject to erosion (ha)	(%)
1. Batangas	256,059	83.1	26. Catanduanes	57,229	39.9
2. Cebu	371,307	76.3	27. Negros Or.	188,723	35.5
3. Ilocos Sur	198,225	73.8	28. Camarines Sur	182,587	34.3
4. La Union	96,565	70.3	29. Zambales	122,899	33.7
5. Batanes	13,439	67.9	30. Isabela	347,596	32.9
6. Bohol	269,074	66.0	31. Nueva Ecija	171,415	31.1
7. Msbate	269,516	66.1	32. Romblon	41,018	30.9
8. Abra	248,102	65.1	33. Bulacan	70,230	26.6
9. Iloilo	337,132	63.5	34. Sorsogon	50,718	24.7
10. Cavite	77,995	60.6	35. Misamis Or.	96,295	24.6
11. Rizal	121,790	58.4	36. Nueva Viscaya	152,279	22.4
12. Capiz	243,079	55.2	37. Laguna	26,298	21.8
13. Marinduque	47,593	51.7	38. Cagayan	191,849	21.4
14. Negros Occ.	385,203	49.7	39. Misamis Occ.	44,101	21.3
15. Tarlac	147,005	48.4	40. Quezon	236,526	19.8
16. Ilocos Norte	158,196	46.7	41. Bataan	26,021	19.4
17. Pangasinan	241,667	46.2	42. Cotabato	358,277	15.6
18. Mindoro	460,951	45.7	43. Lanao	98,388	14.7
19. Antique	121,879	45.6	44. Camarines	30,789	14.3
20. Bukidnon	334,610	42.7	45. Zamboanga	202,508	12.0
21. Pampanga	91,259	42.6	46. Davao	205,287	10.5
22. Mt. Prov.	600,731	42.5	47. Samar	145,595	10.5
23. Sulu	116,807	41.5	48. Palawan	114,810	7.8
24. Leyte	327,905	41.0	49. Surigao	46,104	5.7
25. Albay	104,160	40.5	50. Agusan	48,147	4.5
Total Philippines				8,895,948	29.9

Source: Mamisao, Jesus P. 1949. Soil Conservation Trends in the Philippines (provided by Miranda 1978).
*In order of percentage of area subject to erosion.

greatest single cause of accelerated erosion in the Philippines. Many of these are forest roads. Serrano and Suan pointed out that 3.8 million hectares of forest and alienated land were released for urban use or cultivation during the five-year period from 1970 to 1975. This represents great acceleration compared with a total of 4.4 million ha of forest cleared during the preceding thirty years.

Available literature suggests that Taiwan may be far ahead of most tropical countries in the formulation of conservation policies for agriculture. This island has an area of 35,759 km^2 of which 70 percent is hilly (above 100 m in altitude) to mountainous, with many peaks over 3000 m (JCRR/MARDB 1977). The high erosion hazard throughout the island is illustrated by the annual average precipitation of 1000 to 4000 mm, with the heaviest falls in the mountainous areas. With a current population of over 16 million and a policy of self-sufficiency, agriculture is being compelled to expand beyond the present 917,000 ha of less rugged land into the steep foothill country, which is very susceptible to erosion. In response to the recognized urgency of severe soil erosion problems, a soil conservation program was started in the mid-1950s to formulate effective control measures for these areas. Among the few quantitative figures on the magnitudes of soil loss were those given by Hsu et al. (1977). These authors measured soil losses of up to 186 Tm/ha from plots established on 18° slope and planted to various crops during the 1975 rainy season. However, a general assessment of the extent of soil erosion in the different sections of the country is not available. Dils (1977) discussed some aspects of erosional problems in watersheds located in all three major zones—the Plains, the Intermediate, and the Mountain Forest zones. He indicated the continued seriousness of erosion, sedimentation, and landslide problems in all three, citing as an example the recent release of 65,000 ha of forest for use in farming within the Intermediate zone. Of these, only 5000 ha are subject to conservation measures, but nearly



Map 12. Rainfall patterns of the Philippines. (Bureau of Soils and PCARR 1977)

Table 14. Degree and extent of soil erosion in areas licensed to timber companies within the Agno River basin, Philippines

	Erosion class*											
	None 0		Slight 1		Moderate 2		Severe 3		Extreme 4		Total	
Timber license holder	Area(ha)	%	Area(ha)	%	Area(ha)	%	Area(ha)	%	Area(ha)	%	Area(ha)	%
Heald Lumber Company	4,756.4	22	216.2	1	2,810.6	13	11,026.2	51	2,810.6	13	21,620.0	100
Benguet Consolidated Inc.	6,334.8	14	-		4,532.0	10	6,798.0	15	27,645.2	61	45,320.0	100
Itogon-Suyoc Mines, Inc.	1,418.4	24	-		413.7	7	827.4	14	3,250.5	55	5,910.0	100
Northeastern Timber Development Corporation	5,075.4	22	-		1,384.2	6	4,844.7	21	11,765.7	51	23,070.0	100
Pangasinan National Resources Development Corporation	8,516.4	47	-		2,899.2	16	1,630.8	9	5,073.6	28	18,120.0	100
Tarlac Timber Corporation	10,047.8	66	-		-		-		5,176.2	34	15,224.0	100
Santa Cruz Development Corporation	3,722.3	29	-		2,182.2	17	3,337.3	26	3,593.2	28	12,835.0	100
Zambales Timber Company, Inc.	1,448.7	61	-		-		95.0	4	831.3	35	2,375.0	100
Southern Zambales Lumber Company	178.5	15	-		-		1,011.5	85	-		1,190.0	100

Source: Evaluation report on logging operations and other land-use practices in the Agno and Pampanga river basins: Concomitant effects on Central Luzon floods. September 1972--BFD. After Miranda 1978.

* None (0) -- no apparent erosion; Slight (1)--slightly eroded (<25% of surface layer removed); Moderate (2)--moderately eroded (25% to 75% of surface layer removed); Severe (3)--severely eroded (>75% of surface layer to part of subsoil removed); Extreme (4)--very severely eroded (all of surface layer and 75% of subsoil removed).

all require intensive measures for erosion and flood control. Road construction is blamed for most of the accelerated erosion and landslides in the Mountain Forest zone, because of poor or nonexistent surface drainage and vegetative protection.

Rainfall Erosion in Tropical Australia, Papua New Guinea, and Pacific Islands

Northern Australia and Papua New Guinea

In Australia, a continent in which 50 percent of the area receives less than 250 mm of rainfall per year, wind erosion is a serious problem in some areas. However, erosion by water is possibly more serious because it affects the more agriculturally productive areas (Downes 1963). For example, a study of three catchments in northern Queensland (Douglas 1967) gave the following suspended sediment loads in Tm/km²/yr:

	Upper	Lower
Barron River Catchment	8.5	20.4
Davies Catchment	3.03	5.63
Millstream Catchment	9.23	18.4

In the Windera district of Australia most of the land is sloping and, with the intense summer rainfalls, sheet and rill erosion may occur. Even on slopes greater than 2 percent and on alluvial flats with slopes greater than 0.2 percent, protective measures must be employed to reduce erosion (Stone 1975). Increased numbers of cattle, coupled with poor management, have resulted in serious overgrazing and erosion in parts of Alice Springs, the Barkly Tableland, and the Kimberley district (Sturtz et al. 1975). Erosion is severe in parts of the east and west Kimberley region of northwestern Australia and results primarily from overgrazing of cattle (Fitzgerald 1975). About 25 percent of the Northern Territory, which has an extent of 1,348,000 km², shows accelerated soil erosion that is particularly serious in the upper valley watercourses in the wet monsoonal area of the Darwin and Gulf districts. Nearly 30 percent of the Ord–Victoria River and the Barkly districts, both primarily cattle-raising areas, were subject to active erosion during the 1960s. In addition, gully erosion was evident in 20 percent of the Ord–Victoria River district and about 10 percent of the Barkly Tableland. Degeneration of pastures through excessive grazing pressure has generally been followed by accelerated erosion (Walter 1971). Recognizing the importance of soil erosion problems, each of the states within Australia has established government departments for soil conservation (variously named Soil Conservation Service, as in New South Wales, or Soil Conservation Authority, as in Victoria).

Papua New Guinea is subject to considerable rainfall erosion by virtue of rugged terrain and ample precipitation. According to Bleeker (1975), 14,130 km² of the total land area of 470,000 km² are subject to strong erosion and 83,810 km² to very strong erosion. In high rainfall areas, where logging has been by selective cutting, soil erosion has been limited. However, where large areas of clearfelling occur, as in the Gogol Timber Project at Madang, the erosion problem increases (Lamb and Beibi 1977). By sampling stream water, the rate of denudation was found to be 137 Tm/km²/yr in central Papua (Turvey 1974).

Pacific Islands

Data from the Pacific Islands, other than Hawaii, are scant. Nevertheless, hazards of water erosion are severe on most of these islands by virtue of aggressive climates, rugged topography, and frequent exploitation of land on a massive scale, such as that associated with the establishment of sugarcane plantations. Among accounts of Fiji (Cochrane 1967; Ward 1965) it has been noted that the main island of Viti Levu is undergoing widespread erosion. The foothills behind Nadi are covered with landslides that give the region a scarred and barren look. There is widespead sheet wash and slipping in the Yavuna area. Burning is a major problem and, coupled with overgrazing, has caused pastures to degenerate. Although burning is prohibited by legislation it is widely practiced. The severity of soil movement and siltation can be appreciated from Cochrane's (1967) statement that fifteen years ago coastal vessels plied the Ba River; today trucks drive on what was then the river. In the kingdom of Tonga, composed of some 150 islands in Polynesia, soil erosion problems are reported to be mild because of porous soils, good internal drainage, and flat topography. However, soil degradation through fertility problems seems to be increasing, particularly in Ha'apai. This is attributed to both shortened fallow periods associated with shifting cultivation practices and the increased planting of coconut palms (Maude

1970). According to Fox and Cumberland (1962) the steepland soils of Samoa have also been depleted of nutrients and are badly eroded.

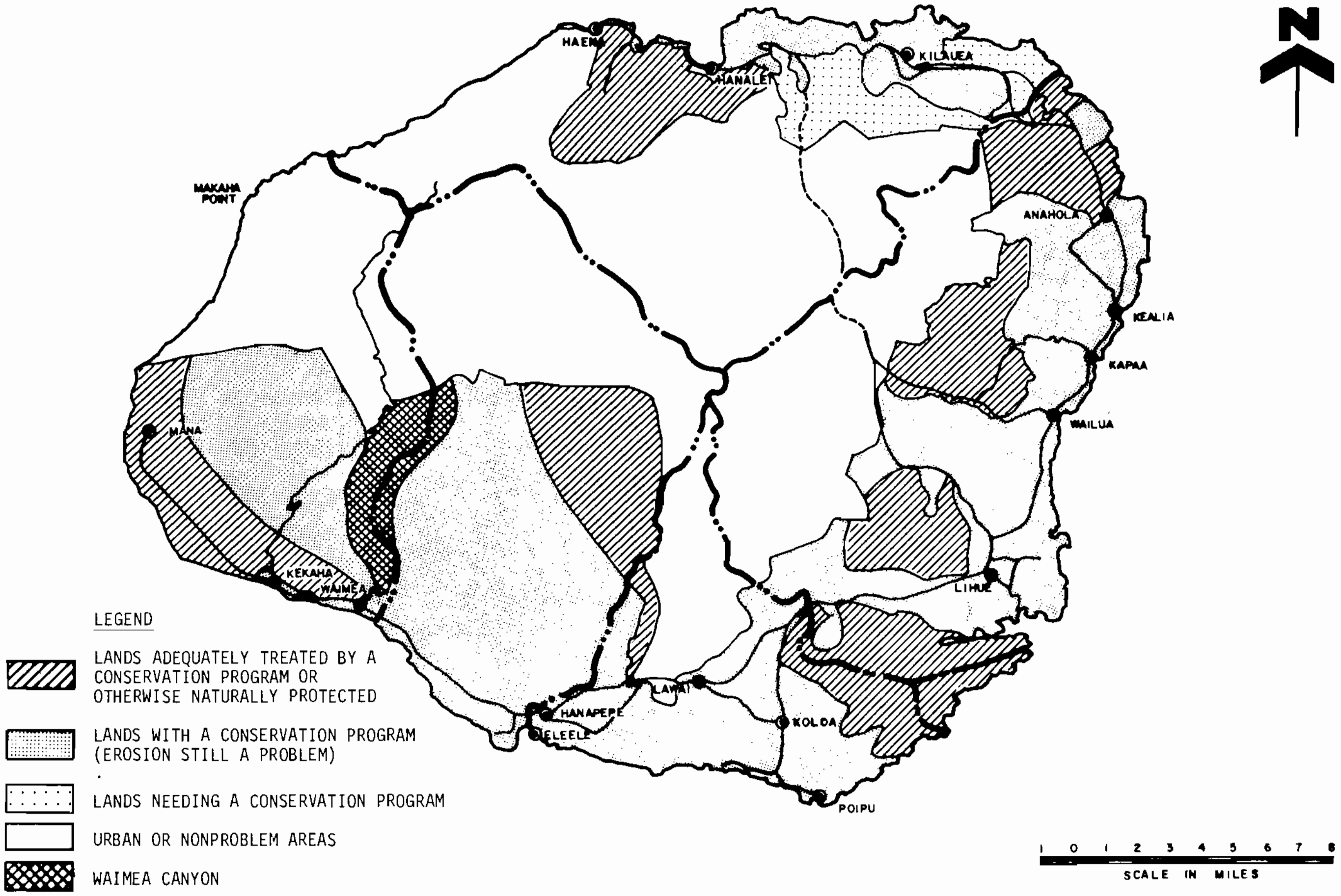
In an analysis of the agricultural potential of Guadalcanal, Hansell and Wall (1970) subdivided the island into seven regions. Both the Kaichui Land Region and the Itina Land Region are largely mountainous and are subject to moderate to severe erosion. Although the Paru Land Region experiences landslides and undergoes gully erosion, the agricultural potential is good. The Tetere Land Region is mainly level so that drainage and flooding problems are more evident than erosion.

In Hawaii, soil erosion has been a problem since the introduction of domesticated animals. Following the discovery of the islands by Europeans in 1778, goats left by Captain Cook multiplied rapidly. Cattle and sheep were introduced shortly afterwards by Vancouver. A thirty-year ban on the slaughter of these animals caused an inordinate increase in their populations and the eventual destruction of the koa forest. Barren, eroded hillsides and soil slips, as well as dusty alluvial plains, became evident (Christ 1960). Reforestation has restored much of the watershed to forest, although introduced trees (such as *Eucalyptus, Acacia,* and *Casuarina* spp.) now form approximately half of the forest cover on Oahu and several other islands. With the advent of statehood in 1959, construction activities of all types increased, and in turn accelerated soil erosion. Concerned agencies clearly became alarmed when the major bays on Oahu (such as Kaneohe and Pearl Harbor) rapidly became receiving basins for soil lost from adjacent slopes. An inventory of land use conducted by the Hawaii Agricultural Extension Service (1961) showed that over 55 percent of the land was in forest, with about 9 percent in cropland, 19 percent in pasture, and 17 percent in other uses. The projection for 1975 was for slight rises in crop and pasture use and a corresponding drop in forest. The opinion has been expressed that even the forests are not without problems. Because *Andropogon virginicus,* an introduced grass on Oahu, does not utilize water efficiently, it has been considered a cause of slumps on steeper land. This contributes indirectly to the undesirable silting in Kaneohe Bay (Mueller-Dombois 1973). El-Swaify and Cooley (1980, 1981) reported the results of several years of monitoring soil losses from agricultural lands, and indicated that in most cases, the average annual soil loss from these sources remains within the acknowledged tolerable limit of 11 Tm/ha/yr. Another survey of nonpoint sources of pollution, including erosional sediments, was recently completed (TCNSPC 1978). Maps 13–18 show the estimated current erosion status of various districts on the major islands. Land that is actively eroding represents approximately 2.6 percent of the overall land mass of the major islands. A breakdown of soil loss magnitudes estimated within the above survey is given in Table 15.

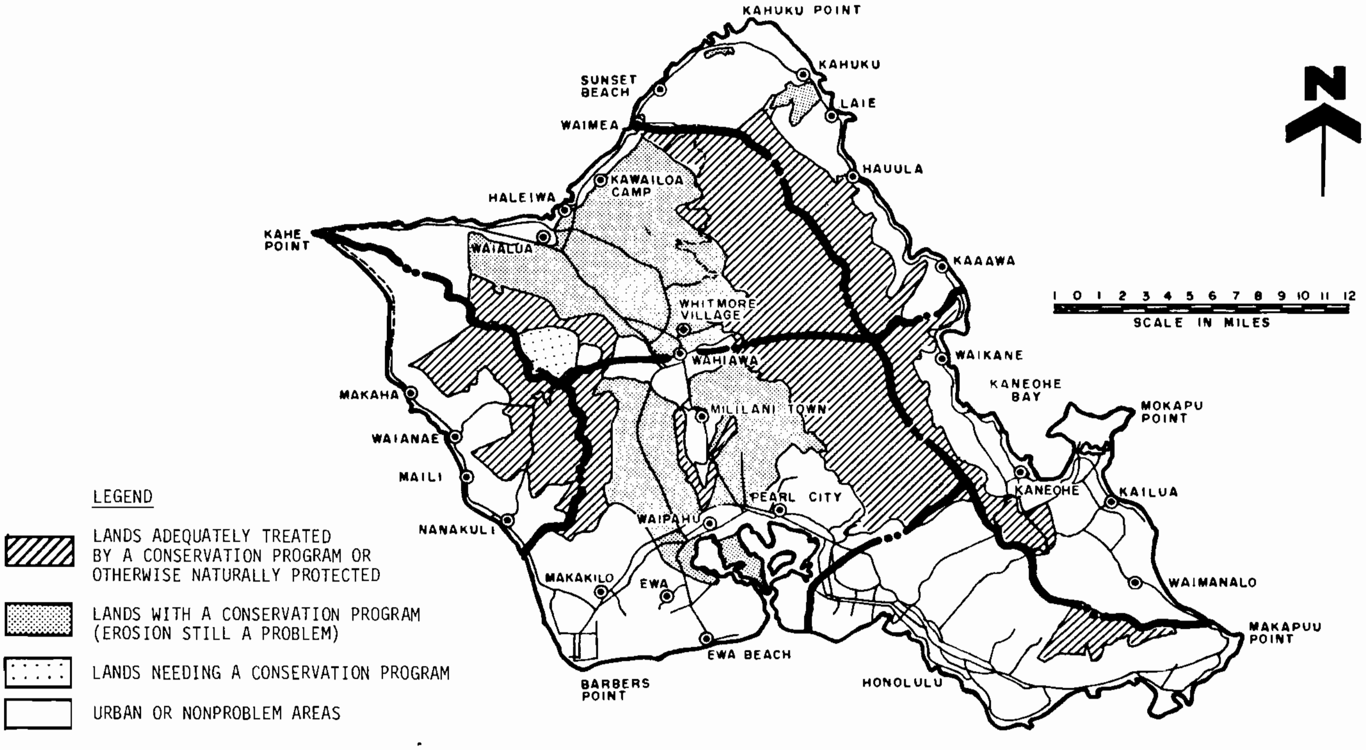
In Kauai, the oldest island in the chain, the Waimea area includes the famed Waimea Canyon. A relatively small proportion of Oahu is judged to be actively eroding. As the bulk of the population resides on this island, much of the land is urbanized. The large Ewa area embraces Pearl Harbor and has considerable land under sugarcane and pineapple, as has the Waialua area. On Molokai, much of the damage experienced in the Hoolehua district has been initiated by excessive grazing. On Maui, in the huge Makawao area, much of the erosion is in gulches and barren areas not covered in the survey. The same situation exists in the Nahiku district. Hawaii—the "Big Island"—is approximately twice the size of all the other islands in the chain combined. The Hamakua district receives the highest rainfall on that island, whereas the Ka'u and particularly the Kona districts are characterized by less rainfall. The latter has minimal erosion rates. Only about 1 percent of the land of the Big Island is actively eroding. However, thousands of acres are devoid of soil and vegetation because of recent volcanic lava flows. Therefore, the reported percentage of land eroding from this island, and the state as a whole, is misleading as it underestimates the extent of erosion in usable lands.

Rainfall Erosion in Tropical South America

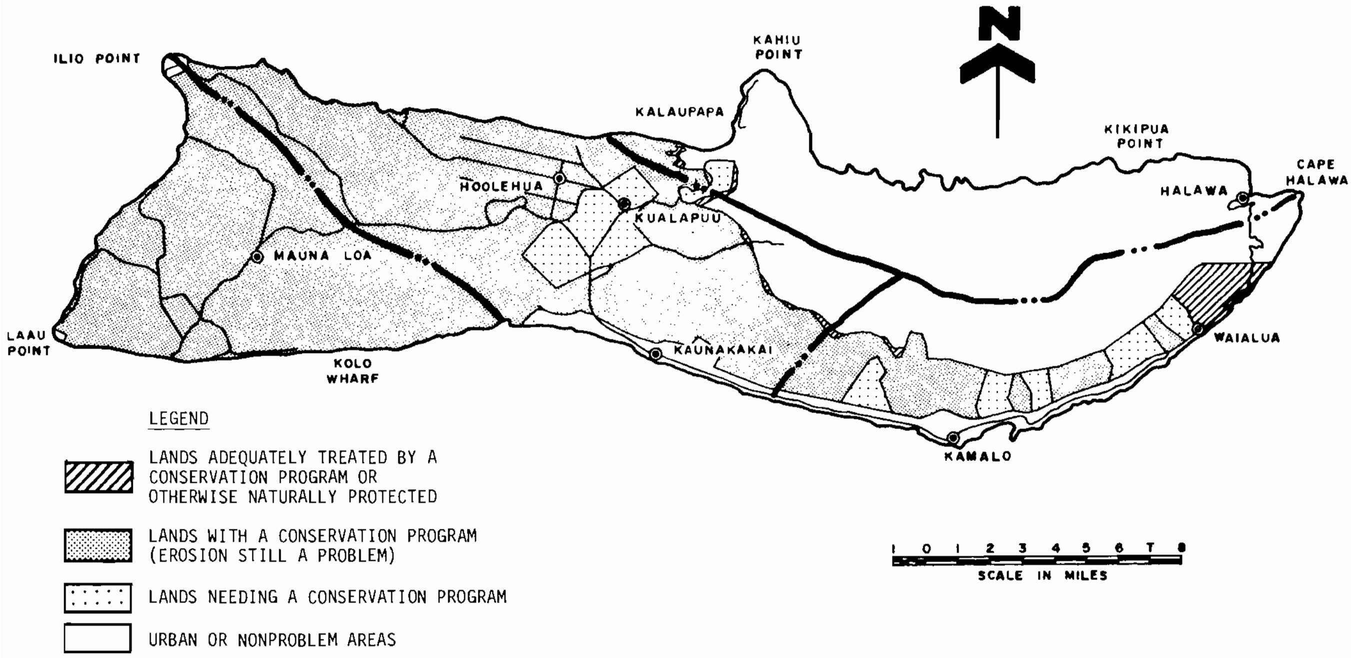
The Andes buttress the western portion of the South American continent like a great misplaced spine (Eckholm 1976). Starting in Venezuela, these mountains comprise major portions of Colombia, Ecuador, Peru, and Chile, coming within 60 miles of the Pacific Ocean in some places. To the west of the Andes, from Ecuador southward, lies an arid coastal desert; the jungle of the Upper Amazon stretches to the east from the foothills and comprises large areas of Colombia, Ecuador, Peru, Bolivia, and Brazil. Unlike the Rockies of North America and the European Alps, the Andes are densely populated, which is a major cause of erosion problems. For example, the population of Peru has increased from 4 million to 15 million people since the turn of



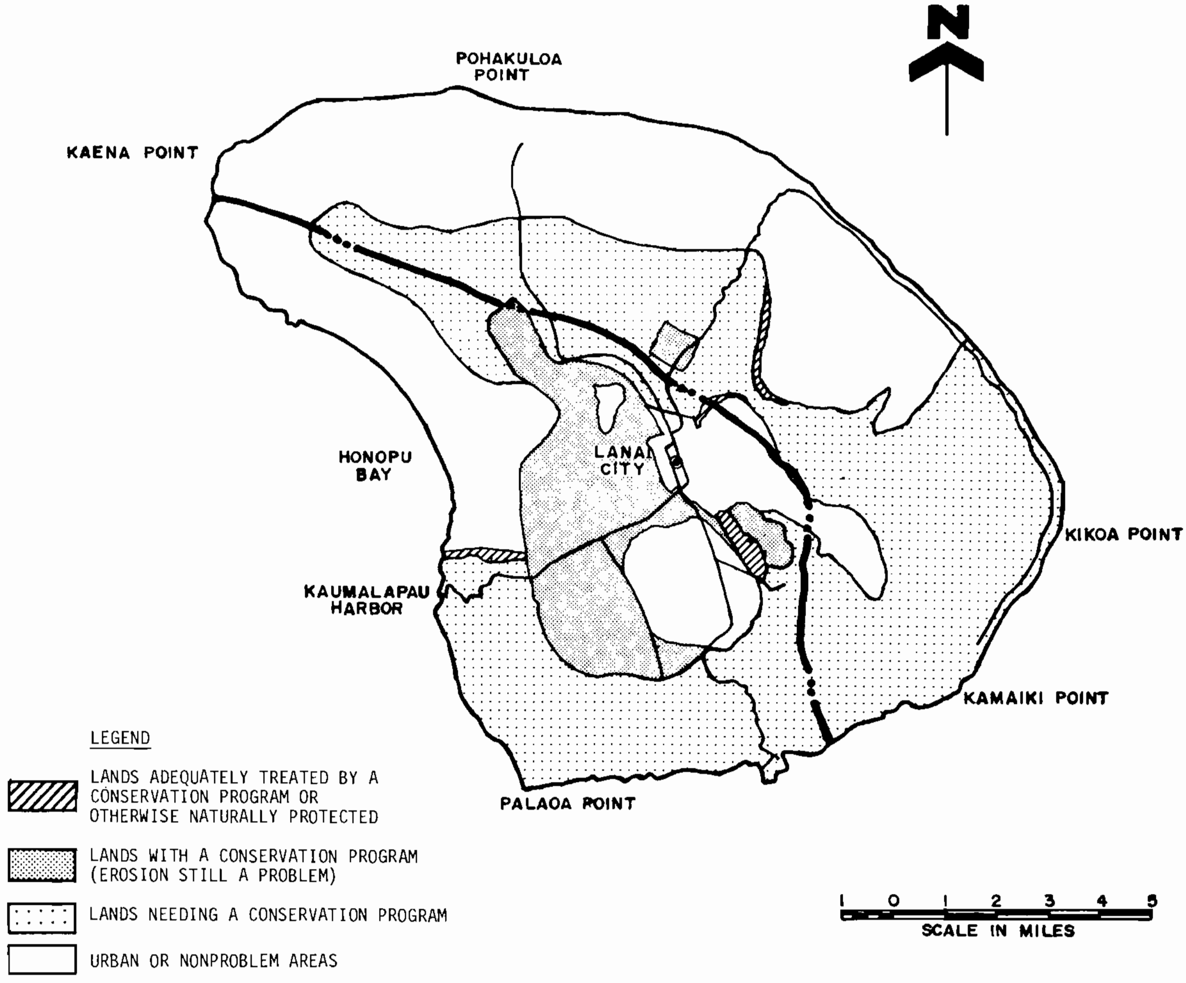
Map 13. Estimated erosion status of the island of Kauai, Hawaii. (Technical Committee on Nonpoint Source Pollution Control 1978)



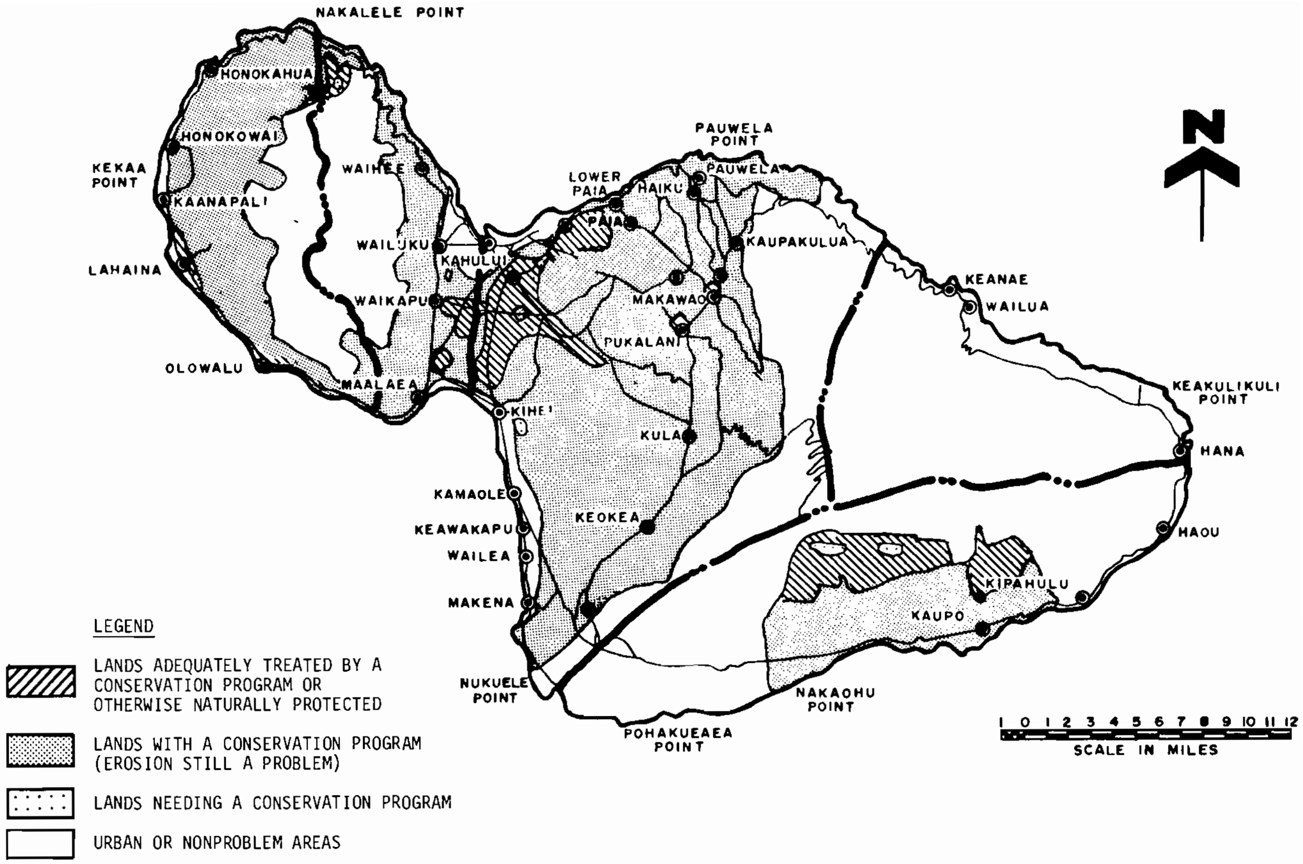
Map 14. Estimated erosion status of the island of Oahu, Hawaii. (Technical Committee on Nonpoint Source Pollution Control 1978)



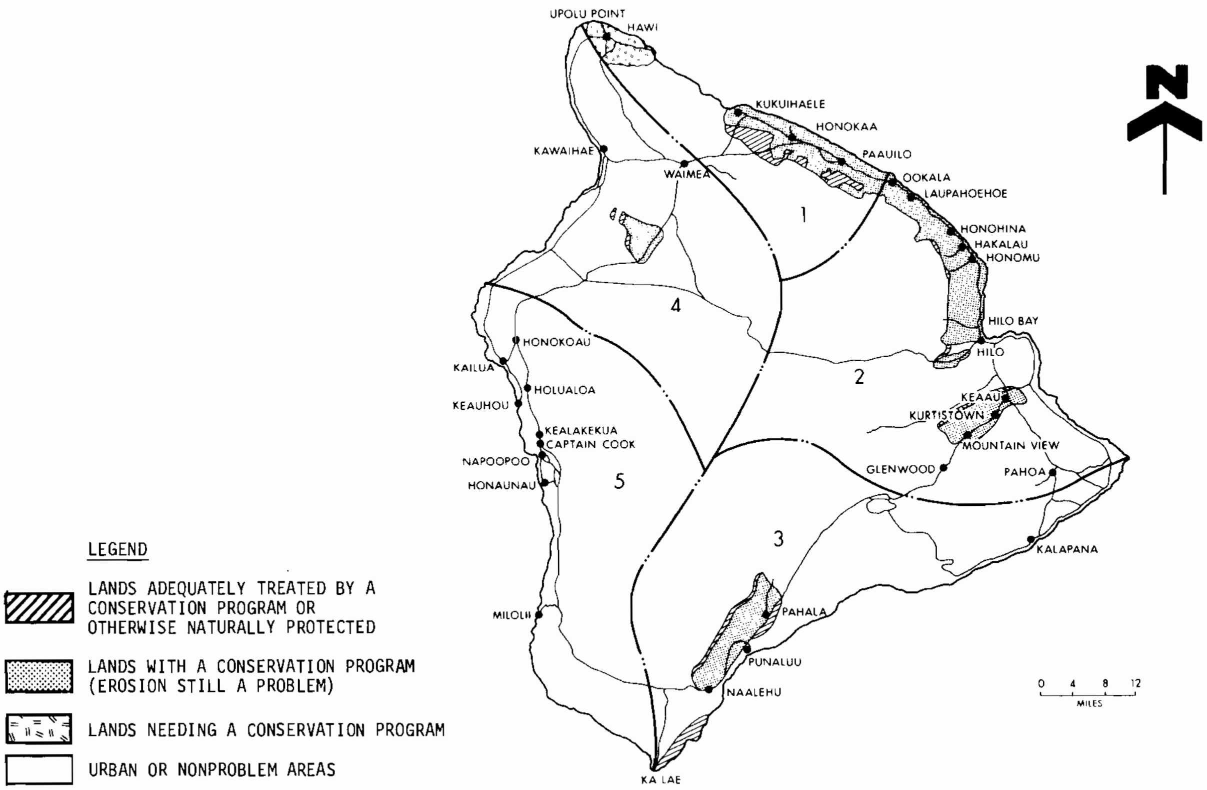
Map 15. Estimated erosion status of the island of Molokai, Hawaii. (Technical Committee on Nonpoint Source Pollution Control 1978)



Map 16. Estimated erosion status of the island of Lanai, Hawaii. (Technical Committee on Nonpoint Source Pollution Control 1978)



Map 17. Estimated erosion status of the island of Maui, Hawaii. (Technical Committee on Nonpoint Source Pollution Control 1978)



Map 18. Estimated erosion status of the island of Hawaii. (Technical Committee on Nonpoint Source Pollution Control 1978)

Table 15. Actively eroding areas and erosion rates for the Hawaiian Islands

	Area (ha)	Actively eroding area (ha)	Rate of erosion (Tm/ha/yr)
Kauai	143,300	7,892	
Hanalei	38,000	607	5.5-27
Lihue	33,500	971	5.5-82
Koloa	21,000	243	5.5-82
Waimea	31,040	3,238	5.5-136
Kekaha	19,870	2,833	5.5-136
Oahu	156,415	3,116	
Kahuku	16,350	243	5.5-55
Kaneohe	21,056	364	5.5-55
Honolulu	25,739	405	5.5-27
Ewa	36,896	850	5.5-82
Waianae	19,709	445	5.5-54
Waialua	36,665	809	5.5-136
Molokai	67,381	11,659	
Wailau	14,103	251	5.5-57
Kamalo	13,335	2,671	5.5-136
Hoolehua	24,261	3,221	5.5-136
Maunaloa	15,682	5,516	5.5-163
Lanai	36,463	10,361	
Maunalei	19,429	5,673	5.5-136
Kaumalapau	17,034	4,688	5.5-136
Maui	188,548		
Lahaina	24,808	545	0.27-79
Wailuku	21,085	498	0.27-57
Makawao	70,700	---*	0.27-79
Nahiku	28,774	---*	0.54-95
Kaupo	43,181	660	0.27-106
Hawaii	1,045,852		
Hamakua	103,731	3,642	0.27-218
Hilo	261,068	3,238	0-82
Ka'u	252,478	81	0-163
Kona	200,832	minimal	0.27-27
Kohala	227,743	1,214	0-136

Source: TCNSPC 1978 (modified).
* Soil movement may be disproportionately large compared to the negligible acreages of eroding areas accounted for in this inventory.

the century. Deteriorating conditions in the mountains and lack of agricultural land reforms are causing great numbers of people to move to the disease infested humid lowlands where modern medicine is rendering the jungles habitable. Table 16 shows an assessment of the extent of erosion associated with various climatic and vegetative zones in the continent, as made by FAO (1954*c*). A breakdown of actual and potential erosion in various countries is not available in the literature. However, the following is a synthesis of available information from scattered sources.

Colombia

Geologically, Colombia is characterized by a largely mountainous western half; the eastern half is rolling plains. Nearly thirty years ago soil erosion throughout the country was estimated at 426 million Tm/yr (Suarez de Castro 1952). The accelerated form of erosion was attributed to the clearing of forest. Prieto Bolivar (1951) equated river sediment loads with the awesome loss of 250–300 ha/day of arable soil. Little measured erosion occurs on the alpine soils (over 2700 m elevation); however, erosion occurring on subalpine soils at 2100–2700 m altitude is severe. These areas are largely cultivated in pasture or corn (FAO 1954*b*). In central Colombia, coffee plantations and pasture are the prevailing land uses. The pastures are burned regularly and are subject to sheet erosion. Landslides also are a common feature of the area. On the plains of eastern Colombia, the grasses on predominantly lateritic

Table 16. Relationship between climate, vegetation, and soil erosion in Latin America

Climate	Vegetation	Soil erosion
Super humid	Rain forest	Slight or moderate land slips and some deep gullies in unstable terrain
Humid	Forest	Moderate and severe on sloping lands where cleared and cultivated to row crops
Subhumid moist	Tall grass	Generally, none to moderate on smoother lands. Moderate to severe on sloping lands in warmer climates
Semiarid	Short grass	None to moderate on smooth lands in cooler regions; moderate and severe over large areas, particularly in Mexico
Arid (intermingled with semiarid)	Desert plants (chiefly desert shrubs and cactus)	Moderate and severe--much geological erosion accelerated by overgrazing

Source: FAO 1954c.

soils are extensively grazed. Erosion is localized in the vicinity of water holes, but elsewhere in this region erosion was not considered a problem due to the sparseness of settlements (FAO 1954*b*). In contrast, erosion is severe in the mountain valleys and basins, where the capacity of the land to carry cattle is often exceeded. Erosion is also significant in regions of specialized farming that grow cacao, tobacco, and coffee. Erosion problems associated with coffee planting are generally attributed to this crop being cleanly cultivated on steep slopes in Colombia. Suarez de Castro (1951*a*) reported soil losses of 500 Tm/ha/yr from a cleanly weeded coffee plantation of 43 percent slope. An adjacent plot under "good care" with a 53 percent slope had negligible soil loss. In another study it was found that soil losses from a bare plot harrowed monthly were 253 Tm/ha/yr in 14 months; on a covered plot the loss was 3.02 Tm/ha in the same period. The damage from erosion was illustrated by the later finding that corn planted on the heavily eroded soil required four times as much land area to produce the same yield as corn grown on the slightly eroded site (Suarez de Castro 1951*b*). The drier parts of the Colombian Andes are characterized by soils that are developed from volcanic ash and quite susceptible to erosion. A comparative study of two profiles from the dry area and an Andosol profile from a humid area indicated that the intense gully erosion in the drier areas may be a result of thin A and B horizons in very sandy-textured and very clayey-textured soils, respectively, as well as clayey subsoil of low resistance (Jungerius 1975).

Ecuador

Despite its small area, Ecuador includes the three major regions that characterize all countries of northwestern South America. These are a sloping coastal belt from the Pacific Ocean, the steep highlands of the Andes, and the Amazon basin. Foglino (1965) estimated that 1.77 million ha (or 54%) of the 3 million ha in the high sierra are eroded. He also estimated that 1 million ha or 40 percent of the low and flat prairie lying to the west are undergoing serious erosion. Severe soil erosion has been recorded in the northern sierras, where sheep pasturing is practiced. Enhancement of erosion occurs because the soil in this region is underlain by an impermeable layer at 1 m depth. As a result, the soil tends to saturate and form a slurry that flows easily during heavy rains. North of Quito is an erosion-prone, semi-arid area devoted to sheep grazing. The Conservation Foundation (FAO 1954*b*) stated that moderate erosion rates follow overgrazing on the steep, brushy lands of the southern sierra. In contrast, no accelerated erosion was identified in the

Amazon basin due to protective forest cover. Lal (1977*d*) noted that unmaintained remnants of Inca terraces, which originally served as conservation measures by channelling and releasing large volumes of water at certain locations, have led to recent severe gully erosion in the highlands.

Peru

As with the other northwest South American countries, Peru is divided into a coastal zone, the Andean highlands, and the Amazon lowlands. The coastal belt is arid, but snow-fed Andean streams permit numerous oases on alluvial pans, where cotton, rice, and sugarcane are grown. Here, where nearly a third of the population resides, accelerated erosion is minimal but geological erosion is spectacular, resulting in well-established gullies and canyons. The highland zone is unique in that there are longitudinal troughs between the individual ranges of the Andes that isolate the population clusters. Moderate erosion is observed throughout the inhabited parts of this zone where subsistence agriculture as currently practiced is considered more primitive than the former Inca agriculture. In some areas bedrock is exposed and agriculture is impossible; overgrazing by sheep, llamas, and alpacas has resulted in surface wash and gullies. By 1954 no conservation measures had been introduced and yields of potatoes, grain, and corn were reported to be very low (FAO 1954*b*). This report noted further that the eastern slopes and Amazon lowlands were settled sparsely, in isolated clusters. Shifting agriculture was practiced to some extent, and where sedentary agriculture was found, sheet erosion had occurred. The only agriculture found in the Amazon basin was along river banks, where field peas and rice were grown on flood sediments with little accelerated or geological erosion observable at the time. Using Fournier's index, Low (1967) estimated that over half of the Andean areas of Peru have a potential annual erosion rate of 1000–1500 Tm/km^2 (Table 17). He indicated that the highest potential rate (5000–7000 $Tm/km^2/yr$) is assigned to the Ceja de Selva region of the Andes, whereas the lower jungle and Huallaga Valley have the lowest rates. The potential average for the country as a whole was estimated at 1501 $Tm/km^2/yr$ (15 Tm/ha/yr). Actual erosion was observed by Seubert (1975, cited by Lal 1977*d*) to be a serious problem in the Amazon region where shifting agriculture is gradually being replaced by continuous cultivation. Seubert found that clearing by bulldozer reduced infiltration rates to 0.5 cm/hr compared to 10 cm/hr on an area cleared by burning alone. The study was made in the area of Yurimaguas where the average annual rainfall is nearly 3000 mm/yr.

Table 17. Estimate of potential erosion in the Andean region of Peru, using Fournier's climatic coefficient

Erosion range ($Tm/km^2/yr$)	Area (km^2)	Percent of total area
0-1,000	216,040	16.88
1,000-1,500	670,620	52.38
1,500-2,000	215,544	16.85
2,000-3,000	95,400	7.45
3,000-4,000	34,580	2.70
4,000-5,000	31,700	2.48
5,000-7,000	16,120	1.26

Source: Low 1967.

Bolivia

Although Bolivia is called an Andean republic, half of its area lies within the Chaco Plain on the lowlands. The southeastern part of the country is the altiplano, a nearly barren, high plateau. Tropical rainforest occupies the north, while savannah is present in the south. Most agriculture in the altiplano is at 3600 m elevation or higher, where quinoa, wheat, and potatoes as well as sheep are raised. Erosion is locally severe. Nomadic sheep pasturing has caused serious erosion in the steep country east of Oruro. Commercial agriculture is concentrated in a limited number of intermontane valleys where irrigation is required, and erosion is not a problem except where pasturing is practiced on the adjacent mountains (FAO 1954*b*). More recently, Chase (1976) has labelled erosion a major problem in Bolivia. He attributed the increased problem to the lack of trees and the resulting lack of replenishment of organic soil material.

Paraguay

This country, where 75 percent of the population lives within 100 miles of Asuncion, is most fortunate to have large areas of undeveloped arable land to sustain immigration or relocation of farmers from other sections of the country. Soil erosion is noticeable mainly in the central part of the country and results chiefly from clean cultivation of sloping land during the rainy season. The deeper soils developed from basalt are quite resistant to erosion, whereas soils formed from granite or limestone are more prone to erosion and more difficult to restore to productivity when eroded. Western Paraguay, known as the Chaco, has a very low population density. Cattle raising and extraction of quebracho (a tannin-rich extract) from the quebracho tree are the main occupations. The area east of the Paraguay River is in virgin hardwood forest and not subject to erosion (FAO 1954*b*). No later accounts of the extent of erosion in the country are available.

Brazil

With a larger area than the continental United States, Brazil contains a wide variety of climates and landforms. Therefore, erosion problems will be discussed separately for the various geographical regions.

Southern Brazil. The Conservation Foundation reported serious erosion in the wheat-growing area of this region (FAO 1954*b*). Some erosion was also reported for the sloping lands planted in corn. Farming systems using crop rotation as practiced by European immigrants were less subject to erosion. However, losses of soil fertility due to prevailing intensive cultivation were documented. Rawitscher (1948, cited by Lal 1977*d*) noted no serious erosion problems on the deep acid red loams of this region, except on overstocked ranges, under bare fallow and clean-tilled coffee plantations, and where uncontrolled burning has been practiced. More recently, concern has been expressed over the nearly irreversible degradation of some areas in southeast Brazil as a result of serious erosion induced by combined deforestation and heavy rains (Oliveira 1970). In the coffee and cattle zone of Sao Paulo the soils were reported to be chemically poor but physically excellent (FAO 1954*b*). It was observed that the soils have traditionally been "mined" by planting coffee, sometimes interplanted with the subsistence crops of the field workers. Cotton was planted after the land became exhausted from coffee culture. When yields from this crop fell, the farmers moved on to more fertile land. However, even as early as 1954, virgin land became scarce and the need arose to stabilize farming operations by implementing good conservation practices. In addition to the cropping sequence noted, a forest-rice-cotton rotation has been practiced (FAO 1954*b*). No information was given on the relative merits of the two distinct cropping sequences. Lal (1977*d* citing Marques et al. 1961 and Bertoni 1966) designated the areas of the central and western portions of the state of Sao Paulo as erosion prone due to their characteristically rolling topography. Annual soil losses of up to 21.1, 9.5, and 21.5 Tm/ha/yr have been found for sandy Bauru, Terra Roxa, and sandy Botu Catu soils, respectively, when used for cultivation of annual crops. Under similar rainfall (≈ 1200 mm) the sandy Bauru soil revealed higher soil losses (53 Tm/ha/yr) than the Terra Roxa (21 Tm/ha/yr) in the absence of control measures.

Central Brazil. Mostly shifting agriculture and pasturage for beef and dairy cattle are practiced in this region. The soils are reddish lateritic clays or sandy clays and were presumed to withstand poor farming practices for long periods (FAO 1954*a, b*). Soil fertility was noted to be partially restored after fallowing. As early as 1954, northwestern Sao Paulo, Rio de Janeiro and southern Minas Gerais had completed the coffee cycle with the characteristic decline in yields resulting from fertility losses. Poorly managed coffee plantations have suffered severe erosion, particularly on the steep slopes that dominate this area, where soils are derived from granites, gneiss, and schists (Lal 1977*d*).

Northeastern Brazil. This area of the country has a narrow coastal belt that is primarily in pasture, with serious localized gullying present. Adjacent to the coast, a hilly zone with an annual rainfall below 500 mm has shallower soils that do not respond well to fertilization and are unable to support adequate protective vegetation. Where rainfall is greater than 1000 mm, and the highly leached soils respond well to fertilizers, sugarcane is grown. A transition zone receiving an annual rainfall of 500–1000 mm, supports a dense human population that exerts heavy pressures on the land. The interior of northeastern Brazil is a drought area with less than 500 mm of rain annually, where accelerated erosion frequently occurs as a result of overgrazing by cattle and goats.

Western and Northwestern Brazil, including Amazonia. This area is renowned for its vast savannah and rain forest. Mid-century, the Conservation Foundation (FAO 1954*b*) reported only limited local erosion problems related to overgrazing. However, the Amazon Basin is now experiencing one of the great immigrations of people in this century (Eckholm 1976), and roads are being built to speed settlement of the region. Yet the opinion has been expressed that the soils generally are poor and better suited to forestry than agriculture. The 50,000 settlers who by 1976 had moved in along the new Trans-Amazon Highway were reportedly encountering difficulty in sustaining more than a subsistence level of farming

(Eckholm 1976). Bosshart[1] observed that erosion is a serious problem in degrading pastures throughout Amazonia. *Panicum maximum,* which is very productive in southern Brazil, has been seeded extensively on pastures in the Amazon. Since it is a bunch grass and not adapted to infertile soils it does little to stop extensive erosion on farm pastures. The poor management of lands under this grass—primarily the excessive stocking rate—has further aggravated the degradation and erosion problems. Although excessive soil erosion is easily observed throughout the Amazon region, it is only recognized as a problem if roadbeds are washed away. Bosshart also indicated that this is why the Brazilian government has extended contracts to develop methods for revegetating the rights-of-way of highways such as the BK319 from Manaus to Porto Velho.

Venezuela

This is a country of great physiographic diversity. The Venezuelan Highlands form the northeastern extension of the Andes. In the higher western and southern forks of the Andes there is little level land, so that approximately 75 percent of the cultivation occurs on slopes exceeding 25 percent. Shifting cultivation is commonly practiced and erosion has been severe, causing much land to be abandoned. Lands of gentler slope have moderate to severe soil erosion, some of which results from overgrazing. Although the northern and coastal highlands are less rugged, erosion occurs when the land is cleared. On the 10 percent of the area that is relatively level, intensive agriculture is practiced. Shifting cultivation is said to have contributed seriously to erosion problems because the main subsistence crop is corn, which is row cropped up and down slope. This cropping system leads to rapid depletion of nutrients and offers little protection against removal of soil. Pasturing of goats also has been damaging to the soil. The Maracaibo Lowlands are wedged between the branches of the Andes. According to the Conservation Foundation (FAO 1954*c*), only small areas where soil erosion was a problem existed south and west of Lake Maracaibo, but severe erosion existed north of the lake from overgrazing of sheep, goats, and cattle. The Orinoco Llanos is a vast, gently sloping plain stretching from the Andes to sea level. Although cattle were abundant, there was little cultivation so that erosion was insignificant. The Guiana Highlands, in the south and southeastern portions of Venezuela, were little cultivated and sparsely settled. No serious erosion problems existed at the time (FAO 1954*c*). The most important agricultural areas are found in the western plains of Venezuela. The prevailing soils, though they belong to different orders (Entisols, Inceptisols, and Alfisols) all have been found to possess low aggregate stability against direct raindrop impact. This leads not only to high soil erodibility, but also to associated problems of compaction and crust formation (Pla 1977).

Guyana, Surinam, and French Guiana

Three quarters of the land area of the Guianas were still covered with virgin forest and free of erosion as of 1954 (FAO 1954*b*). However in southwest Guyana (formerly British Guiana), the dominantly poor sandy soil is intensively cultivated and was reported to be extremely erosion susceptible; fortunately it represents only a minor area of the country (FAO 1954*b*). In the hinterland of Surinam, large areas are being cleared for agricultural use. Trees are uprooted, felled, or cut off and pushed into windrows. During this process topsoil may be removed and structural deterioration and compaction are evident, with an increase in surface bulk density (from 1.28 to 1.63 g/cm^3), and an accompanying decrease in soil porosity. Both the root elongation rate and the root density of plants are reduced because of impedance resulting from soil compaction (Van der Weert 1974). In addition, revegetation of these areas is uneven and, although the extent of resulting erosion was not mentioned, it must be concluded that the erosion hazard is high when these factors are operative.

Rainfall Erosion in Central America

The terrain of Central America (the area from Mexico to Colombia) is largely hilly or mountainous with abundant steep slopes. Erosion hazards are therefore high, reflecting topographic inducement of erosional processes. This is particularly true for the southern part of the region, including southern Mexico, which is characterized by an annual rainfall of more than 1250 mm. The Conservation Foundation (FAO 1954*a*) presented maps of the extent of existing erosion in this region, as well as in the rest of Latin America. However, because it is not likely that these maps reflect the present situation accurately, they are not reproduced here.

1. Robert P. Bosshart, Instituto de Pesquisas IRI, Matao, Brazil. Personal communication, 1978.

Mexico

The land use situation in Mexico is not promising. Over half (52%) of the country is arid and about a third (31%) is semiarid (Macias and Cervantes 1966). Interestingly, early explorers estimated that 40 to 50 percent of the land was forested. By 1950 this figure had fallen to 10 percent and has continued to decrease since (Sears, cited by Eckholm 1976). Andrade and Payan (1973) maintained that the country is in imminent danger of becoming a barren plain. Half the terrain is over 1000 m in altitude with much of it on steep slopes (Lal 1977*d*). Two main mountain ranges dominate the steep lands of Mexico, the Sierra Madre Occidental, which extends southward from the U.S. border of Arizona and New Mexico to the lowland of Tehuantepec, and a shorter range, the Sierra Madre Oriental, which essentially forms the eastern edge of the high plateau and finally merges with the western range in southern Mexico. Many less extensive ranges and volcanic cones rise from the plateaus and lowlands. However, the dominating feature of the uplands is the system of plateaus and large intermontane basins. Arid northwestern Mexico and the semiarid north central region are both clad in xerophytic shrubs. The lands in the east and the south, which receive enough rainfall to allow establishment of cacti and short grass cover, are extremely susceptible to overgrazing. Thousands of square miles in Mexico (and the southwestern United States) have been severely damaged by moderate to severe soil erosion induced by overgrazing. It is estimated that 12.5 billion m^3 of topsoil have been washed into the sea during the past century. Only 17 percent (34 million ha) of the arable land in Mexico is considered erosion free (Lopez Saucedo 1975). According to Macias and Cervantes (1966), an estimate based on the 1950 census indicated that 10 percent of the land was not eroded, 18 percent had slight erosion, 21 percent was moderately eroded, 43 percent showed accelerated erosion, and 8 percent was completely eroded. The most important cause of this dismal picture is overgrazing by too many domestic animals. Corn, a severe soil depleting crop, is grown on 50 to 60 percent of the arable land so there is an urgent need to develop adequate management techniques to control erosion (Lal 1977*d*). According to the Conservation Foundation (FAO 1954*a*), most permanently damaged soils are the shallow, sloping soils underlain by infertile parent rock or hard impervious layers such as caliche. In the very humid mountain lands, the dominant forms of erosion are land slips and slides rather than sheet and gully erosion. Historically, although the Mayas must have practiced intensive agriculture on the Yucatan Peninsula, erosion was probably not critical. Soil removed from the slopes filled in the basins. Overall, soil erosion in the Yucatan Peninsula was classed as slight or nonexistent (FAO 1954*a*). However, recent population pressures are giving rise to less shifting cultivation and more localized and continuous use of land for cropping.

Guatemala

A large population of Indians constitutes nearly 70 percent of the total population of Guatemala. They practice subsistence agriculture and raise primarily corn, the staple of their ancestors, while commercial plantations of coffee are found in the higher lands. Soil erosion is moderate from both forms of agriculture. Banana plantations in the Atlantic lowlands have begun to shift to the sloping piedmont and coastal plain between the highlands and the Pacific Ocean. According to the Conservation Foundation (FAO 1954*a*), soil erosion was slight both on the abandoned lands and on the banana plantations. Erosion hazards under different management techniques have been reported by Cardona and Deger (cited by Lal 1977*d*).

Belize

Formerly called British Honduras, Belize is a country of forests, and forest products such as mahogany, chicle, rosewood, and logwood are important to the economy. There is little commercial agriculture. Shifting cultivation (called milpa) is practiced by the Maya Indians who constitute about 25 percent of the population. Moderate to severe erosion was nearly always reported on the sloping cornfields before they were abandoned and allowed to grow brushy cover (FAO 1954*a*).

El Salvador

In El Salvador tropical deciduous forest originally covered 90 percent of the land surface. Today the forest is completely cleared for grazing, plantation agriculture, mining, charcoal manufacture, and subsistence agriculture. Soil erosion is rampant, especially on the extensive hillsides (Daugherty, cited by Eckholm 1976). Seventy-seven percent of the land suffers accelerated erosion and El Salvador is considered by some to be one of the most environmentally devastated countries in the New World

(OAS 1974, cited by Eckholm 1976). Soon after forest clearing, most of the soils, which are derived from volcanic ash, basic lava flows, or alluvium, had a high level of fertility. Centuries of cultivation in corn and beans have exhausted much of this fertility and brought severe erosion to the steeper slopes (FAO 1954*a*). It is expected that erosion problems are now more grave in view of the continuing population explosion, acknowledged as the most intensive on the mainland of the Americas (Daugherty, cited by Eckholm 1976).

Honduras

In contrast to its neighbor El Salvador, Honduras has a relatively low population density. The people are clustered in the intermontane basins where they carry on subsistence farming of corn, wheat, beans, and rice. Coffee is a major commercial crop. The Conservation Foundation (FAO 1954*a*) reported moderate to severe soil erosion on the sloping land, whereas only small areas in the banana plantations on the Caribbean Coast have soil erosion problems. More recent accounts of the extent of erosion in this country are not available.

Nicaragua

In Nicaragua the main population resides in the Pacific lowlands and extends southeastward from Lake Managua and Lake Nicaragua to the Caribbean Sea. Subsistence agriculture (based on corn) and coffee plantations are found on the hilly lands. Northern Nicaragua is generally high-altitude land and is sparsely settled by people engaged in stock raising or shifting cultivation. The Conservation Foundation (FAO 1954*a*) reported that the broad lowland in the northern part of the country was also thinly populated and used for scattered shifting cultivation, and that attempts to introduce commercial agriculture into the region, such as banana cultivation, have failed. Their erosion survey indicated little, if any, erosion in the country in general.

Costa Rica

This is another densely populated country with an agricultural population concentrated in an intermontane basin. Farms are small and devoted to raising coffee, corn, potatoes, and other vegetables as well as dairy cattle. Although there has been intensive land use, erosion was designated as slight or moderate by the Conservation Foundation (FAO 1954*a*). Experiments were conducted over a three-year period on a set of plots, referred to as the Turrialba plots, located in the Reventazon Valley region (Ives 1951). It was noted that due to the well-aggregated, highly permeable clay loam (grayish brown) soil on these plots, virtually no soil loss occurred under grass cover or on a contoured, intertilled crop. However, a 410-mm rainfall on 6 December 1949 (a once-in-twenty-five-years storm that exceeded the capacity of the recording rain gauge; nearby stations recorded 250 mm of rain in less than 10 hours) caused soil losses of 125 Tm/ha from a bare plot with 16 percent slope. Quite oddly, a bare slope of 45 percent yielded no soil loss whereas a similar grass-covered plot produced a soil loss of 84.6 Tm/ha! Recently cattle ranching has spread in Costa Rica to supply the North American market. According to Spielmann (1973 cited by Eckholm 1976), this is forcing the small farmers onto poor quality, easily eroded lands while the per capita beef consumption of the local population drops.

Panama

This country has the smallest population of any in Central America and is about one-third urban. Fortunately, most of the country is forested and shifting cultivation is practiced. The Conservation Foundation (FAO 1954*a*) reported that large estates were not numerous although there was some commercial agriculture in bananas, coconuts, and cacao. In general, soil erosion was not considered serious as the dominant subsistence crop is rice rather than corn and the heavy forest growth serves as excellent cover.

Rainfall Erosion in the Caribbean Islands

''Every Commonwealth Caribbean island now recognizes soil erosion as one of its most important agricultural problems'' (Ahmad and Breckner 1974).

In Haiti, which shares an island with the Dominican Republic, soil erosion is now recognized as a major cause of poverty and is stated as the country's principal problem. Less than 9 percent of the countryside is now wooded and the previously forested mountains are desolate. The best lands are owned by a few wealthy farmers and sugar corporations. Consequently, the increasing population of peasants is continually searching for new lands to cultivate and is forced up the mountain slopes onto the poorer lands (Eckholm 1976). Rampant erosion has exposed much of the bedrock with outcrops forming more than 50 percent of the land surface. Ahmad (1977) observed that, despite the seriousness of the problem, no conservation measures are being followed. Haiti is therefore a classic example of continuing severe land degradation, perhaps more so than any other country in the world.

The adjacent Dominican Republic does not suffer as serious an erosion problem as Haiti because the natural vegetative cover has been maintained. However, severe erosion is found in the Cordillera Central, the Cordillera Occidental, the Cordillera Septentrional, and the Cibao Valley (Ahmad 1977).

In Puerto Rico soil erosion is a major problem because of hilly topography and dense population (347 persons/km^2 according to the United Nations 1977). Only about one fourth of the land has less than 15 percent slope whereas one fifth has over 60 percent slope (Lal 1977*d*). About one quarter of the land surface is in woodland or brush and erosion in this portion is not a major hazard (Barnett et al. 1972). A study of red clay Latosols (Oxisols) and shallow brown clays showed that natural, fallow plots with 40 and 45 percent slopes, give a six-year soil loss average of 284 Tm/ha/yr (Smith and Abruna 1955). Similar but desurfaced plots produced average losses of 340 Tm/ha/yr during the same period. Under various cultivated crops and mulching treatments, these losses were significantly reduced. Barnett et al. (1971) reported that soil losses under simulated rainfall (adjusted to 9% slopes and extrapolated to an annual basis) were 31 Tm/ha, 6.7 Tm/ha, 31 Tm/ha, and 247 Tm/ha for Catalina-Cialitos clay, Humatas clay, Juncos clay, and Pandura loam, respectively. These data were consistent with an earlier study (Bonnet and Lugo Lopez 1950) which gave the relative "erosiveness" (erodibility) of Puerto Rico soils based on dispersion and erosion ratios. These authors reported that the soils ranged from very resistant (such as the Catalina clay of the uplands) to very susceptible (such as Gray-Brown Podzolics).

The most complete study of soil erosion on the island of Trinidad, to our knowledge, was published over 35 years ago (Hardy 1942). In this study the island was divided into six geographical regions. The Northern Range is generally rugged mountainous country. In 1942 the mountains were still under virgin rain forest but since then the foothills have been deforested and exploited agriculturally by peasant farmers. Sheet and gully erosion were both documented in this area; landslides occur during heavy rainstorms, and contributing to the problem was the burning associated with shifting cultivation. The Northern Plain is devoted to plantations of sugarcane or cacao as well as peasant rice. Sheet erosion is prevalent except in such areas as forested portions of Las Lomas and the swamps and forests. The Central Range, mostly in forest reserve and cacao plantations, suffers some sheet erosion but more from landslips and land creep. Hardy (1942) further noted increased evidence of soil erosion on the Madeleine Sugar Company land in the Southern Plain. Soils were described as a black Rendzina and a pale red acidic soil, the latter particularly vulnerable to landslides or soil creep. Loss of topsoil was estimated at 1¼ inches (>3 cm) in the cacao soils and 2½ inches (>6 cm) on the sugarcane soils. In the Southern Range, erosion was evident in the cacao plantations that replaced original forest. Hardy (1942) also noted at the time that the Cedros Peninsula or toe of Trinidad was still heavily forested and not subject to erosion from rainfall. Bell (1973) suggested the existence of serious erosion problems on teak plantations in the Central Range of Trinidad. Lack of cover in the understory from repeated fires was considered the main cause of the problem. Experimental plots from a representative 11-year-old pure teak forest produced soil losses of 153 Tm/ha/yr—nine times as great as found on a mature natural forest (16.90 Tm/ha/yr). The value of vegetative cover was demonstrated in a watershed study in the Northern Range in which soil losses from a pineapple plantation were 0.399 Tm/ha versus 0.046 Tm/ha with pangola grass (Alleyne and Percy 1966).

For the small island of Tobago, soil erosion was important 35 years ago primarily in the Castera and Mason Hall districts (Hardy 1942). The mountainous areas of Tobago are vulnerable to erosion, but fortunately the northern and wettest end of the island is under original forest or permanent tree crops. Erosion is a more serious problem further south. In the Castera-Parlatuvier area, where the soil is very thin, much of the land has been abandoned. On the windward side of the island, where clearing by burning is still practiced for ground provisions and such crops as tomatoes and corn, sheet erosion, gullying, and soil slumping are evident. The Mason Hall–Les Coteaux district remains the worst-eroded area of the island. Here, degradation of the soils began 100 years ago with the cultivation of sugarcane, which was ultimately abandoned. Today, the soils undergo frequent intensive cultivation by peasant farmers. Fires are not used judiciously, with the result that erosion of unprotected soils frequently occurs during the torrential downpours of the rainy season. The drier parts of this area now resemble a desert while the wetter areas are covered with scrub. Fortunately, the parent rock in this area is quite friable and is easily worked to support one or two crops every few years (Ahmad and Breckner 1974).

Jamaica, an island of 4000 square miles (>10,000 km²) and 2 million people, has long been exploited, as have other areas in the humid tropics. The level and gently sloping lands are maintained in large holdings with monocrop agriculture. The poorer lands, which are mountainous with shallow soils, are subject to accelerated erosion as a result of poor agricultural techniques practiced by peasants. In Westmoreland Parish (Stark 1964*a*) in the western part of the island, deforestation and small farms with clean cultivation have caused severe erosion of the shale hills. On the plain below, flash floods cause damage to the sugarcane. A similar situation exists in Hanover Parish (Price 1960). Denudation of the slopes in St. Elizabeth Parish (Stark 1963) has exposed bare rock. Bauxite soils and erodible soils on shale in Trelawney Parish are also subject to erosion (Barker 1970). Here, and in the Parish of Manchester, clean weeding of yam and ginger plantings results in severe erosion, slumping, and gullying. Badly eroded limestone rubble is in evidence in the Parish of Manchester (Stark 1964*b*). Attempts are being made to replant with tree crops and other crops not requiring clean cultivation. In Clarendon Parish (Finch and Jones 1959), as in other locations on Jamaica, small land holdings on the hilly slopes—already difficult to control due to land-tenure problems—are continually becoming smaller through inheritance, and are badly eroded. The Parish of St. Ann (Barker 1968) has similar problems due to removal of trees from the slopes for making charcoal, clean weeding of yams and ginger, and high erodibility of soils derived from shale. The two eastern parishes, Portland (Finch 1961) and St. Thomas (Morgan and Baker 1967), have similar erosion problems. The mountain areas in Portland Parish are subject to sheet erosion which discolors the streams. In the Rio Grande Valley, erosion has completely washed away all soil originating on shale deposits.

St. Vincent is the world's principal supplier of arrowroot starch (Watson and Spector 1958). Cotton and groundnuts are also commonly planted. However, these three crops contribute to a severe soil erosion problem because they are cleanly cultivated during a lengthy period of their growth (Ahmad 1977). As on other islands of the West Indies, the size of land holdings is decreasing because of inheritances, making soil conservation measures more difficult to apply.

Soil erosion is severe in the mountainous interior of St. Lucia. Avalanches occur on the steep terrain and banana plantations are responsible for much soil erosion. The clays, including allophane, are presumably very susceptible to erosion. Gully erosion is common, often starting on footpaths. However, sheet erosion is even more damaging as it occurs on almost all sloping lands in St. Lucia. Because no erosion control measures are employed by small farmers on the hillsides, the problem continues unsolved (Stark et al. 1966).

The economy of the island of Barbados is based on sugarcane agriculture. On the flatter coral soils erosion is insignificant, but on the uplands of St. John's Valley it is a serious problem (Vernon and Carroll 1965). Landslips are induced by the action of spring water lubricating deep slip planes, and result in destruction of trees, crops, houses, roads, and bridges (Cumberbatch 1969). It has been stated that 70 percent of the Scotland District is threatened by erosion, while 11 percent is already severely eroded (Kon 1964, cited by Cumberbatch 1969). Reclamation of eroded soils has been undertaken but many of the mechanical farming practices have led to more landslides and sheet erosion, although sugarcane has been beneficial for soil protection.

The widespread accelerated erosion found on the leeward coast of Dominica results from poor agricultural practices. Landslides occur on soils containing smectites, but in general the high permeability of the soils and the natural forest cover limit widespread erosion (Lang 1967).

St. Kitts, about 65 square miles in area (168 km²), is virtually monocropped to sugarcane, whereas the smaller island of Nevis (36 square miles or 93 km²) is much poorer and mainly in cotton and coconuts. The worst erosion in St. Kitts is found on latosolic soils growing vegetables—due to the practice of heaping the topsoil into mounds for planting. Erosion has been reduced in the mountainous areas by conserving forestlands (Lang and Carroll 1966). Poor farming practices, coupled with soils derived from smectoids, have resulted in substantial topsoil loss (Ahmad 1977). Where cropping continues on the infertile subsoils, degradation is occurring rapidly. Furthermore, cotton is the principal crop and is clean cultivated, contributing to wind and sheet erosion (Lang and Carroll 1966).

Antigua is blessed with a more gentle topography and lower rainfall than many islands of the West Indies, with the result that erosive forces are less severe. However, soil losses occur even on gentle slopes in sugarcane and cotton. Severe gullying has occurred in the Piccadilly area on what was previously good cotton land, and some erosion is occurring on the whole island, except for the alluvial plains (Hill 1966). Barbuda has less rainfall than Antigua (Hill 1966) and agriculture has not been too successful.

The economy of Grenada is based on two tree crops, cocoa *(Theobroma cacao)* and nutmeg *(Myristica fragrans)* and, since these provide more cover than annuals, erosion is reportedly low (Vernon et al. 1958, cited by Ahmad 1977). The deep soils are inherently high in fertility. Conversely, Carriacou has been severely eroded over most of its area. Soil loss down to bed rock is noted (Vernon et al. 1958, cited by Ahmad 1977). The causes were listed as land clearing and poor husbandry with both crops and livestock.

CHANGES IN THE EXTENT OF RAINFALL EROSION AS A RESULT OF CURRENT POPULATION AND ECONOMIC PRESSURES

As reviewed in several instances in the preceding section, increasing population pressures are responsible for ever-increasing deforestation, as more (frequently marginal) land is sought for cultivation or fuel wood. Such unmanaged expansion not only depletes the forests as valuable watersheds and fuel reservoirs, but also gradually eliminates the most effective protection against water erosion on steep slopes. Where slopes exceed 60 percent (as often happens), protection by natural vegetation is essential. As shown in Table 18, forestlands can be as much as 2000 times more effective than alternative land uses for stabilizing the soil against erosion. Accordingly, massive damage can be caused by large-scale timber operations, such as those contemplated or underway in the Amazon Basin by K. K. Ludwig of New York (around the Jari River in northern Brazil) or by Georgia-Pacific, the largest producer of wood products in the Amazon, from its 260,000-ha purchase (Eckholm 1976). The situation is especially serious in Southeast Asia where the Dipterocarp forests continue to be rapidly cut. Often, construction of roads is the most damaging operation in hill-forest exploitation, already a serious problem in Peninsular Malaysia.

The threat to remaining forestlands in the tropics is further accentuated by the growing need of subsistence farmers to expand the land area under crops. In so doing the farmers are no longer solely motivated by the need to meet their increasing demand for food. Recent socioeconomic trends show an increasing desire on the part of small farmers to receive cash from sales of their products. Where forestlands are no longer usable or available, the cropping periods within shifting cultivation cycles are extended at the expense of beneficial fallow periods (chap. 4), thus leading to depletion of soil nutrients, poor crop stands, and serious erosion. Hauck (1974) estimated that such a vicious shifting cultivation cycle is bound to occur when population density exceeds 25 persons/km^2. Eckholm (1976) estimated that in the Bragantina region of the Amazon basin 8 persons/km^2 are "far more than is sustainable by shifting cultivation" due to low fertility and abundant pests. The tropical world is characterized by numerous areas with population densities that far exceed both these figures. Young (1977) claimed that changes from traditional cultivation patterns are now so common that shifting cultivation as a farming system may have already become more the exception than the rule.

Avoiding large population densities by means of schemes involving population shifts has recently been in vogue, particularly in Southeast Asia and South America. Quite often, however, forests in expansion areas are not handled wisely and can be completely destroyed, as appears to be the fate of the lowland forest in Peninsular Malaysia (Chim and Soon 1973). The land rush in Sabah is the subject of similar concern. The transmigration scheme in Indonesia, involving population shifts from Java to Kalimantan (Borneo) and Sumatra, is perhaps the most widely publicized of all. The wisdom of these schemes has been questioned for many reasons, a major one being that the soils of Kalimantan, for example, are reportedly[2] extremely acidic and deficient in calcium and nitrogen. It remains to be seen how this land, which is now essentially forestland, will be able to support cultivated crops on a sustained basis without irreversible degradation. In Java where only 11 percent of the land remains in forest, there is urgent need for the reforestation of original forest areas that are now denuded (Thijsse

2. Morgan, Dan. Washington Post, 26 November 1978.

Table 18. Some reported quantitative effects of human activities on surface erosion

Initial status	Type of disturbance	Magnitude of impact by specific disturbance*
Forestland	Planting row crops	100-1,000
Grassland	Planting row crops	20-100
Forestland	Building logging roads	220
Forestland	Woodcutting and skidding	1.6†
Forestland	Fire	7-1,500
Forestland	Mining	1,000
Row crops	Construction	10
Pastureland	Construction	200
Forestland	Construction	2,000

Source: McElroy et al. 1976.
* Relative magnitude of surface erosion from disturbed surface assuming an initial status of 1.
† This low figure may be characteristic of the practice in the United States. It is essential to note that skidding is likely to cause more severe damage in tropical countries, particularly where no precautions against surface soil disturbance are required.

1976). Among the sensitive areas are 17,710 ha of stripped forest on the slopes above the Cimanuk River and the upland areas of central Java (McComb and Zakaria 1971; Partosedono 1974).

Two essential features of twentieth-century agriculture are mechanization and permanent land use. Controversy rages among erosion workers and conservationists over the merits of mechanized tillage versus no tillage and of intensive localized land use versus shifting cultivation. Examples of successes and failures of both traditional and modern systems are readily recognized and have been used by authors to support their respective points of view. The reasons for these discrepancies in opinion include:

1. The lack of distinction between systems that may be adequate for different climates (e.g. humid versus semiarid tropics), where prevailing soils possess widely different fertility levels and productive capacities.

2. Failure to consider differences in prevailing topography (steepness of relief and differences in altitude), on which large scale plantation agriculture and mere subsistence agriculture may not be equally suitable.

3. Disregard for variations in socioeconomic conditions in different regions (prevailing population density, cultural traditions, land-tenure systems, education levels, and family finances) that can limit or prevent successful cultivation.

4. Inconsistent land-use goals and objectives in different tropical countries (utilization of cleared forestlands for cultivation versus wise sustained use of wood from forests, or their outright preservation as watersheds or for environmental stability).

5. The failure to isolate the different management components that contribute to the success or failure of the system under investigation (methodology of land clearing and utilization, including length of fallow period, incentives to farmers for maintaining effective conservation measures, and the extent of any mechanization to be applied).

These land use considerations will be further elaborated in chapter 4.

CHAPTER 3
IMPACT OF RAINFALL EROSION IN THE TROPICS

Documentation of the impact of erosion is often inseparable from documentation of its extent, which was discussed in chapter 2. The most direct impact of erosional processes—the frequently irreversible loss of the soil resource—must be subsumed in any assessment of existing or potential erosion. Four major consequences of rainfall erosion need to be emphasized: changes in farm productivity, damage from uncontrolled runoff and flooding, siltation of water channels and storage reservoirs, and environmental alterations at sediment destinations such as oceans, lakes, or estuaries. Although environmental considerations are much emphasized in the Western World (ARS 1975*a*, 1975*b*), the first three consequences of erosion are presently more important to developing countries. Together with soil renewal rates, the individual or collective contributions of these changes determine the magnitude of "tolerable" soil losses (chap. 1 and Mannering, 1981).

IMPACT OF RAINFALL EROSION ON SOIL PRODUCTIVITY

Two distinct facets must be considered when evaluating the effects of erosion on soil productivity: effects on the (eroded) soil which is the source of sediment, and effects on the soil that receives deposits of erosional sediment. In both cases, detrimental effects generally far exceed any observed benefits.

Productivity Changes in Eroded Soils

The continuing population explosion and accompanying "shrinkage" of land resources show clearly that the impact of soil erosion on farm productivity should be of foremost concern to developing tropical countries. However, only limited data are available on the effects of erosion on crop yield. Riquier (1977), postulating that land degradation may be a continuous natural process (as in "normal or geological erosion"), indicated that soil productivity undergoes drastic changes only upon accelerated degradation due to increased human activity (Fig. 10). Erosion impact may therefore be quantified by expressing the ratio between yields before and after the start of accelerated erosion, or the magnitude of yield decline per unit time in the area subject to degradation. Unfortunately, the data available to substantiate such expressions are almost nonexistent. However, the responses of many crops to other forms of land degradation, such as soil salinization, have been quantitatively assessed, and the concept is equally applicable to soil erosion. It is important to note here that some soil erosion may be necessary to maintain favorable soil productivity; without any erosion, prolonged weathering under tropical conditions might result in the formation of indurated horizons that render the soil profile unfavorable for crop growth (Mannering 1981).

As the limited data available indicate, crop yield reduction due to erosion depends on soil type and depth, topographic setting, initial fertility status, and structural properties of the profile, as well as the type of crop and the rotation system. In extreme cases, rainfall erosion may result in the total removal of shallow soil and complete elimination of productivity. Several cases have been documented where erosion has proceeded to such an extreme. Dunne et al. (1978) estimated that the prevailing thinning rates of soil profiles in the semiarid rangeland of Kenya, where soil formation rates are negligible, will result in little or no soil on the Kilimanjaro lavas within 200 years; on the Basement schists at Amboseli within 400 years; and that even on the more thickly vegetated Athi-Kapiti plains 50 percent of the landscape will be bare within 500 years. Haiti and Nepal have already experienced such extreme rates of erosion.

Even when soil loss is incomplete, erosive rainfall and runoff act first and most effectively to detach

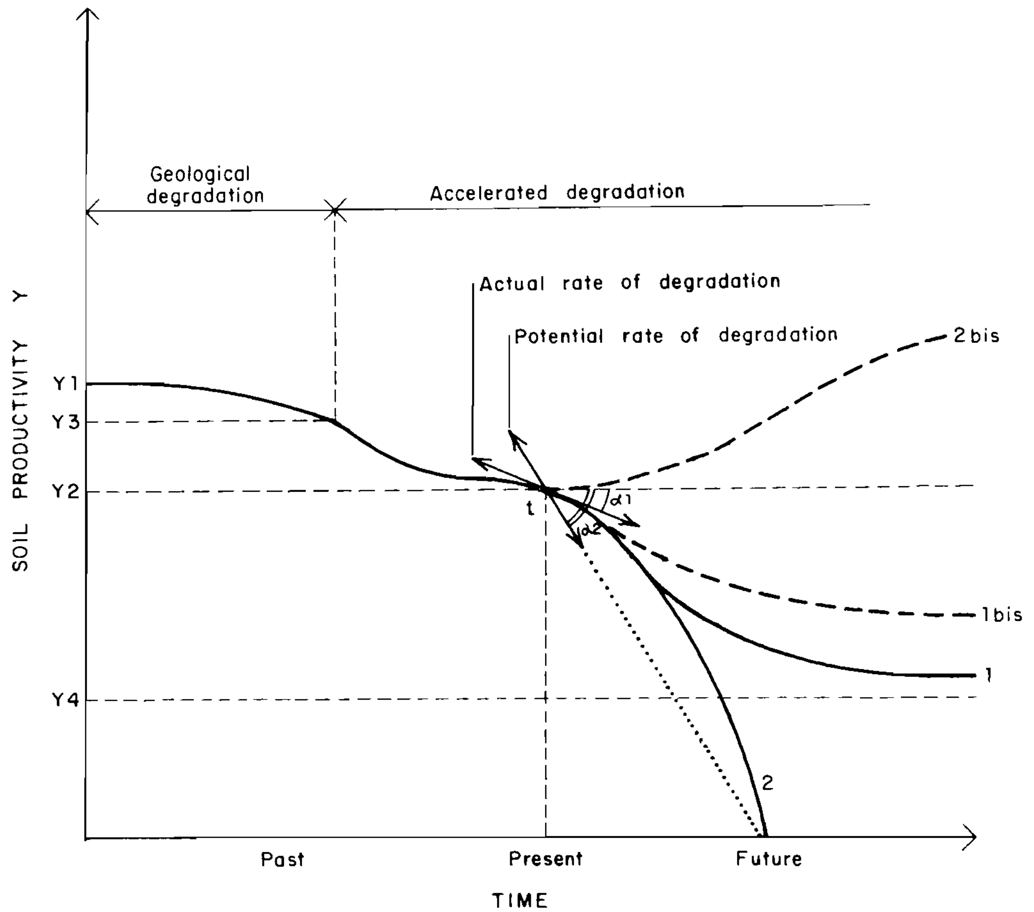


Figure 10. Changes in soil productivity as influenced by the degradation ↔ aggradation processes. Y_1, Y_2, and Y_3 represent soil productivity initially, at present, and at the start of accelerated degradation, respectively. Curve 1 represents the case where cultivation is practiced for several years without fertilization thus leading to an asymptotic low productivity level, Y_4. Curve 2 represents accelerated degradation ending with complete elimination of soil productivity (e.g. complete loss of shallow soil). Curve 1-bis depicts improved management over curve 1 whereby erosion is stabilized after an initial decrease in soil productivity. Curve 2-bis represents successful management resulting in rebuilding of soil productivity. (Riquier 1977)

and move downslope that topmost part of the soil profile which is most favorable to crop growth, both nutritionally and physically. The remaining soil mass is therefore deficient in fertility and deprived of a desirable soil tilth and structure. These two deficiencies together reduce soil productivity. Contrary to frequent references in the literature, crop yield declines as a result of erosion should not be interpreted as due to fertility losses alone. Aside from the low proportion of essential ionic nutrients retained in the lower horizons of profiles of highly weathered soils, such horizons generally lack the organic matter content and the loose, porous structure necessary for uninhibited proliferation of roots, proper aeration, and the ability to store and transmit water efficiently. This explains why rainfall acceptance by eroded soils is considerably less than by the original soils; rainfall acceptance is further curtailed by increased surface sealing due to the action of erosive forces. Lal (1976*d*) documented severe reductions (nearly 20-fold) in infiltration rates of Alfisols after two years of erosion while fallow. He also measured significant reductions in the water-holding capacity of eroded soils, a change that he attributed to selective losses of fine soil particles and organic matter.

The fertility of soil lost to erosion has been investigated by many authors, a few of whom have worked with tropical soils. Moberg (1972) analyzed different profile depth segments of eroded and noneroded or virgin plots of Ferralsols (Oxisols) in Tanzania for major nutritional characteristics (Table 19). Throughout the profiles, he measured significant reductions in pH (to a range possibly allowing for aluminum toxicity), organic carbon (and probably associated nitrogen), phosphorus, zinc, copper, calcium, and magnesium. Moberg concluded that

Table 19. Analytical data from some eroded and noneroded Ferralsols (Oxisols) in Tanzania

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	pH	C (%)	P (ppm)	Exchangeable cations Ca (meq./100 g)	Mg	K	Na	H	C.E.C.	Bases (%)	Zn (ppm)	Cu (ppm)
Profile D 1 (eroded plot)															
0-15	26.6	3.1	70.3	4.51	1.40	6	1.37	0.95	0.15	0.10	12.2	14.8	17.6	1.0	5.7
15-30	27.3	4.2	68.5	4.59	1.34	<2	2.08	1.16	0.11	0.06	11.3	14.7	23.1	0.9	4.1
30-60	34.2	3.0	62.8	4.50	--	<2	1.50	0.70	0.10	0.06	11.8	14.2	16.9	1.1	3.5
60-90	37.4	2.6	60.0	4.48	--	<2	1.21	0.48	0.09	0.05	11.9	13.5	11.9	1.0	3.3
90-150	38.6	2.3	59.1	4.46	--	<2	0.79	0.20	0.14	0.18	12.4	13.7	9.5	0.9	3.3
Profile D 2 (noneroded plot)															
0-15	21.1	3.5	75.4	5.29	2.59	33	5.21	2.05	0.32	0.16	8.3	16.0	51.4	3.5	31.0
15-30	21.7	4.2	74.1	4.78	1.22	5	2.28	1.79	0.18	0.18	8.4	12.8	34.6	0.9	4.4
30-60	21.4	3.5	75.1	4.49	0.98	3	1.76	1.32	0.19	0.22	8.1	11.5	30.2	1.9	4.2
60-90	24.9	4.1	71.0	4.29	0.53	3	1.20	0.58	0.14	0.12	6.6	8.6	23.6	5.5	8.2
90-150	30.6	2.3	67.1	4.51	0.49	<2	1.63	0.44	0.10	0.06	6.7	8.9	25.1	1.6	2.9
Profile D 5 (eroded plot)															
0-15	49.5	25.8	24.7	4.07	1.90	5	2.32	1.36	0.19	0.04	21.7	25.6	15.3	0.7	3.3
15-30	55.5	25.6	18.9	3.88	1.31	<2	0.77	0.25	0.16	0.03	24.7	25.9	4.7	0.8	2.3
30-60	63.8	19.6	16.6	3.88	--	<2	0.69	0.07	0.16	0.03	26.6	27.6	3.4	0.6	2.2
60-90	63.2	18.8	18.0	3.82	--	<2	0.54	0.07	0.15	0.03	29.6	30.4	2.6	0.5	2.3
90-150	60.9	21.5	17.6	3.81	--	<2	0.32	0.06	0.12	0.04	24.4	24.9	2.2	1.5	2.5
Profile Ka II, 1A (virgin land)															
0-15	39.1	25.2	35.7	5.15	2.52	12	6.11	4.04	0.18	0.09	15.5	25.9	40.2	3.3	3.3
15-30	57.2	23.4	19.4	4.17	1.45	3	2.20	0.82	0.10	0.07	21.7	24.9	12.8	0.8	2.5
30-60	64.0	20.8	15.2	4.10	--	4	1.40	0.48	0.10	0.07	25.7	27.8	7.4	0.6	2.4
60-90	60.1	22.0	17.9	4.12	--	3	1.80	0.98	0.11	0.08	21.7	24.7	12.0	1.1	3.1
90-150	65.7	19.0	15.3	4.15	1.11	5	1.52	0.80	0.11	0.08	20.6	23.1	10.9	0.8	3.3

Source: Moberg 1972.

Table 20. Nutrients in runoff from selected plots in conventionally tilled tobacco on three soils in Puerto Rico, 1967

	Humatas clay* (Tropohumult)		Juncos silty clay (Eutropept)		Pandura sandy loam (Dystrandept)	
	Check	Fertilized†	Check	Fertilized†	Check	Fertilized†
Nutrients (kg/ha)						
Nitrogen (N)	0.32	0.41	3.84	9.96	0.02	0.35
Potassium (K)	1.70	1.43	6.01	11.27	0.03	0.39
Calcium (Ca)	17.06	6.13	31.62	78.59	0.08	0.30
Magnesium (Mg)	1.09	0.34	12.24	26.81	0.03	0.07
Sulfur (SO_4)	0	0.10	23.65	62.64	0	0.03
Chlorine (Cl)	0.44	0.34	46.84	107.32	1.61	1.16
Rainfall (cm)	6.1	6.0	6.2	6.9	6.9	7.1
Runoff (cm)	2.0	0.8	3.5	3.6	0.1	0.4
Erosion (Tm/ha)	3.92	0.67	0.31	0.62	0.13	0.40

Source: Barnett et al. 1972.
* Received 11.2 Tm/ha agricultural lime (calcium silicate) several weeks prior to tests.
† 1,120 kg/ha (2.27 kg/plot) of 12-6-16 fertilizer applied broadcast 1 hour before 6.4 cm of rain in 60 min.

such reductions cannot be due simply to direct losses associated with soil removal, but must also result from the enhancement of nutrient leaching in the absence of plant roots which normally keep the nutrients circulating in the profile (recycling). Barnett et al. (1972) reported nutrient losses from a Typic Tropohumult, a Vertic Eutropept, and a Typic Dystrandept from tobacco plots in Puerto Rico under simulated rainfall (Table 20). They showed that losses of nutrients in runoff from check plots were generally lower than from fertilized plots, although certain ions (such as potassium) were equally mobile from both. Based on soil erodibility data (El-Swaify and Dangler 1977), and assuming uniform removal of nutrients with soil depth during erosion, losses of "useful" nitrogen and phosphorus associated with soil organic matter from a tropical Oxisol on 16 percent slope may be estimated to reach 40 kg/ha/yr and 12 kg/ha/yr, respectively (Fig. 11). Experiments with fallow and different crop combinations in the Dun Valley, India,[1] showed that the average annual organic matter and nutrient losses associated with runoff and erosion (31.7 to 291 Tm/ha/yr) ranged from 266 to 2168 kg/ha/yr for organic carbon; 40 to 226 for nitrogen; 2.1 to 70.5 for available P_2O_5; 12.7 to 99 for available K_2O; 57 to 533 for exchangeable Ca; and 25.6 to 103 for exchangeable Mg. Lal (1976*d*) distinguished nutrient losses in runoff water from those in sediments from eroded Alfisols (Figs. 12, 13, 14). He found that the sediments carried the major load of removed nutrients, particularly when soil was left fallow without mulch for surface protection. There are many other studies of nutrient depletion as a result of erosion (ARS 1975*b*) which confirm that serious consequences to crop production are likely because the remaining eroded soils are inadequate to sustain crop growth.

Nutrient losses and the unfavorable physical soil properties that result from erosion are generally compensated in highly developed countries by replenishing the soil with fertilizer and performing corrective tillage in order to sustain high crop production levels. However, in developing tropical countries, this is seldom possible. Indeed, it may be argued, that even highly developed countries cannot continue to afford the high cost of energy (Pimentel and Pimentel, 1979) required to restore optimal soil productivity. Lack of adequate conservation measures and resultant soil losses by erosion are directly translated into losses in crop yields that continue to worsen as long as the soil remains in use; the damage to the soil is often irreversible (Moldenhauer,

1. M. L. Kybri, Central Soil and Water Conservation Research and Training Institute, Dehra Dun, India. Personal communication, 1978.

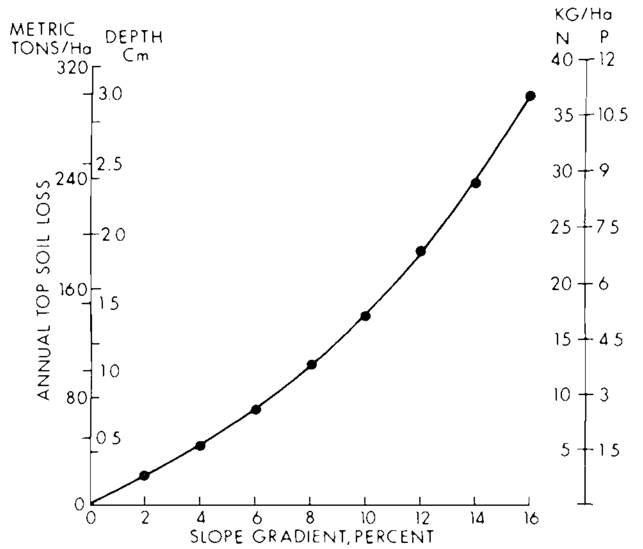


Figure 11. Potential soil and nutrient loss from an unprotected tropical Oxisol (clayey, kaolinitic, isohyperthermic Tropeptic Eutrostox) in relation to steepness of slope. Calculations are based on experimentally measured soil erodibility, on a standard slope length of 23 m, and 1200 mm annual rainfall with a corresponding erosion index of 350 (Wahiawa, Hawaii). (El-Swaify and Dangler 1977)

1980). Figure 15 shows the results of a study simulating the effect of soil loss on corn yield. Although the difference between the estimated yield for Africa ($\approx$ 1000 kg/ha) and that for the United States ($\approx$ 5000 kg/ha) cannot be blamed fully on erosional losses, it can be assumed that such losses represent the major detriment to soil productivity. Huat (1974) cited similar work, conducted by Murray et al. (1939) in Iowa, which showed that in 1936 corn yield gradually decreased from 2963 kg/ha to 1733 kg/ha, as 30 cm of topsoil was removed in increments. Corresponding yields for 1937 were 4919 and 2627 kg/ha. Huat cited similar data from other sources (Stallings 1959; SCS 1948, 1949), which reflected the drastic effects of erosion on yields of maize, oats, alfalfa, asparagus, barley, potatoes, soybeans, and wheat (Tables 21, 22, 23, 24). In his own experiments in Malaysia (Fig. 16), Huat demonstrated serious yield declines in maize as a result of simulated erosion on a colluvial soil. On a different soil in Malaysia, Siew and Fatt (1976) con-

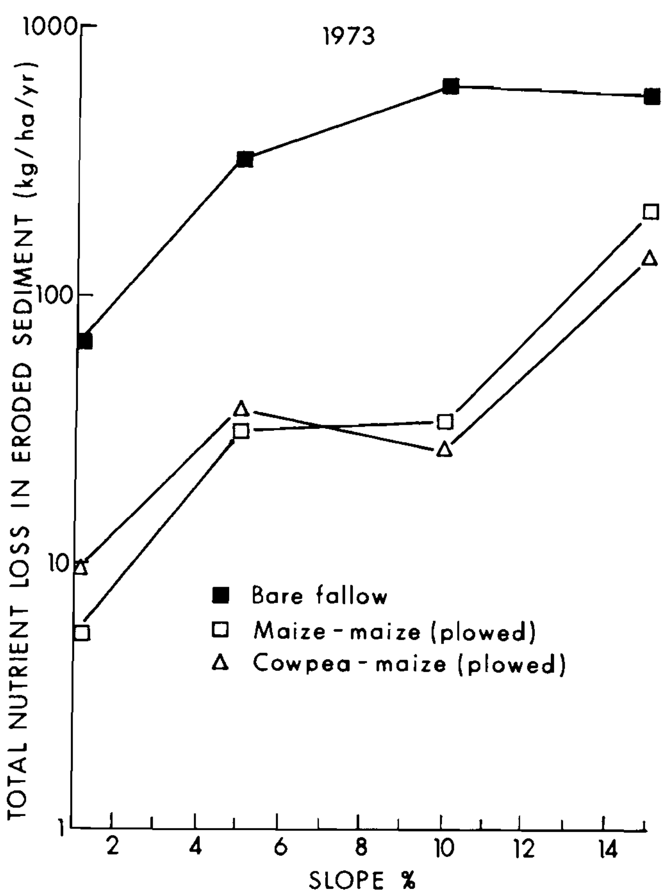


Figure 12. Effect of slope and crop rotation on total nutrient loss in eroded sediments during 1973. (Lal 1976*d*)

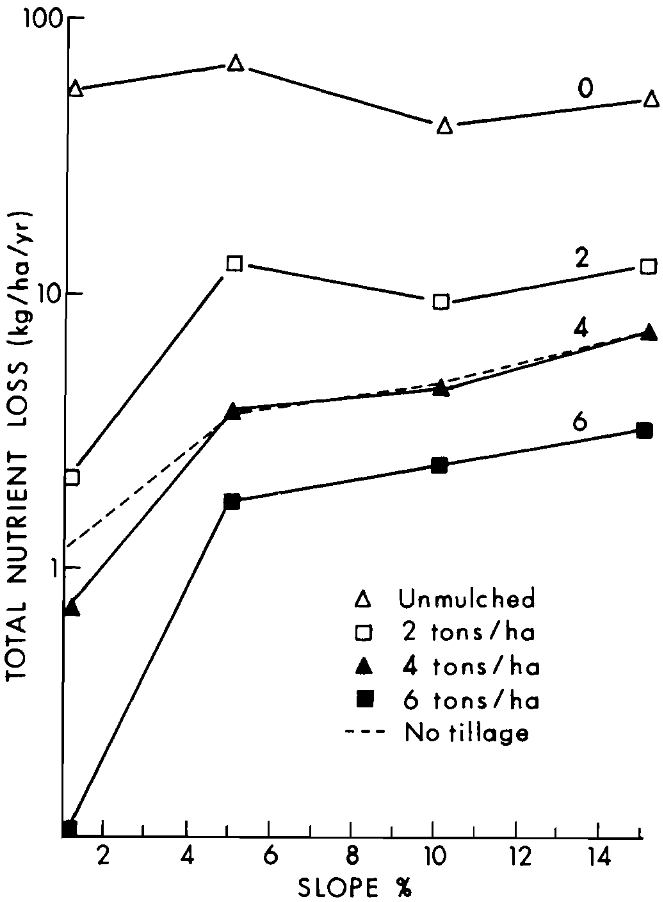


Figure 13. Effect of different mulch rates and slopes on total nutrient losses in runoff water. Zero, 2, 4, and 6 represent the mulch rates indicated in the legend. (Lal 1976*d*)

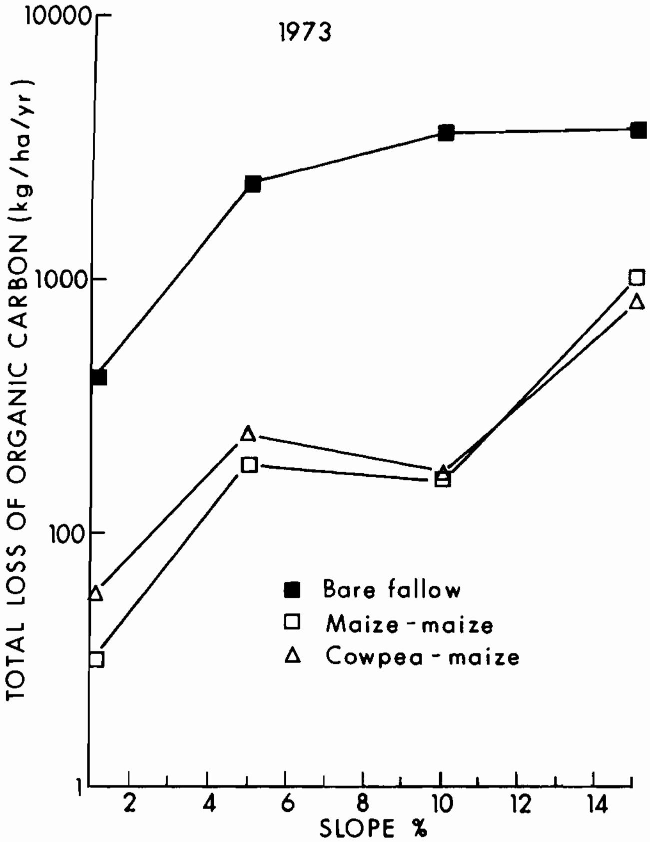


Figure 14. Total loss of organic carbon in eroded sediments, 1973. (Lal 1976*d*)

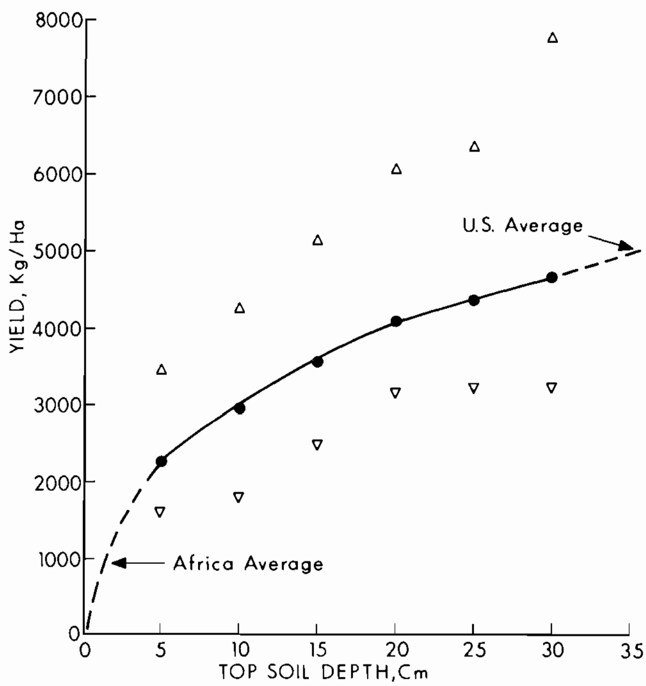


Figure 15. Yields of maize (*Zea mays* L.) in relation to topsoil depth. Data from selected studies on the U.S. mainland. The symbols Δ, •, and ∇ represent upper limits, average values, and lower limits of reported data, respectively. Dashed line represents extrapolation of data. (Modified from Pimental et al. 1976)

Table 21. Effect of depth of topsoil on yields of corn and oats on Tama silt loam, Iowa, United States

Depth of surface soil (cm)	Yield (kg/ha) Corn 1936	Corn 1937	Oats 1937
0-5	1733	2627	--
7.5-10	1565	3857	1661
12.5-15	2180	4305	1949
17.5-20	2739	4584	2236
23-25	2795	4919	2300
28-30	2795	4584	2236
>30	2963	4919	2044

Source: Huat 1974, adapted from Murray et al. 1939.

Table 22. Effect of depth of topsoil on yields of corn and oats on Cecil soil, Georgia, United States

Depth of topsoil (cm)	Yield (kg/ha) Corn	Oats
5.0	601	1584
12.5	795	1958
20.0	1029	2227

Source: Huat 1974, adapted from Stallings 1959.

firmed his conclusion, but to a lesser degree (Fig. 17). They demonstrated by chemical analysis that reduced nutrient content with increasing soil depth was an important cause of the observed yield declines. However, no analysis of physical soil properties was provided. Rimwanich and Na-Thalang[2] reported a reduction of corn yield from an average of 2717 kg/ha when cultivation was on contour (resulting in a soil loss of 0.128 Tm/ha) to 2481 kg/ha when cultivation was up and down the slope (resulting in a soil loss of 5.41 Tm/ha) during the period 1963–1967 in northeast Thailand. Lal (1976*d*) showed a gradual decline in the yield of maize on plowed Alfisols with different slopes over four growing seasons, but did not relate these directly to soil losses from these fields. To simulate the effects of erosional losses, he measured the response of maize and cowpeas to the removal of surface soil layers for two consecutive seasons (Fig. 18). His data showed

2. S. Rimwanich and R. Na-Thalang, Land Development Department, Bangkok, Thailand. Personal communication, 1978.

Table 23. Effect of depth of topsoil on yield of corn

Depth of topsoil (cm)	Yield (kg/ha)			
	Indiana	Iowa	Missouri	Ohio
0	1062	--	894	--
5	1789	3131	1398	--
10	2292	3857	2124	1884
15	2683	4640	2572	2594
20	3019	5422	3019	2857
23	--	--	--	3326
25	3242	5702	3354	--
30	3578	6988	3578	--
33	3745	--	--	--

Source: Huat 1974, adapted from USDA, SCS-TP-75 1949.

Table 24. Relation of crop yields to depths of topsoil

Crop	Yields (kg/ha)	
	0-15 cm depth	15-30 cm depth
Alfalfa	3,960	6,534
Asparagus	231	722
Barley	1,245	2,633
Corn	2,235	3,577
Oats	671	1,073
Potatoes	13,948	17,840
Rye	656	2,068
Soybeans	240	1,078
Wheat	1,019	2,035

Source: Huat 1974, adapted from SCS 1948.

that maize yields were more affected by the removal of the top 2.5 cm of soil than were cowpea yields. Lal attributed yield declines to the unfavorable nutritional and physical properties of the eroded soils and provided rare evidence of the performance of roots in soils subjected to different degrees of erosion (Table 25). Singh et al. (1976) investigated the effects of topsoil removal associated not with erosion as such, but with land levelling required for farm consolidation of rice irrigation projects in the Philippines. They found that scraped soils were nutritionally, physically, and biologically inferior to unscraped soils; all of these deficiencies were effectively corrected by replacement of topsoil or incorporation of organic matter. In contrast, applications of inorganic fertilizer were of only limited effectiveness. Qualitative accounts of the incidence of erosion and its impacts have been given for the Uluguru Mountains of Tanzania (Savile 1947, cited by Temple 1972*a*). The loss in fertility of cultivated soils was reflected in the statement that "A family has to cultivate four or five times as much land as was necesary thirty years ago." Large areas were abandoned and had failed to recover even after forty years of fallow. However, no quantitative fertility loss data are available from the Ulugurus. Anderson (1962), cited by Temple (1972*a*) stated that clean-weeded coffee brought about "a marked loss of organic matter in a few years". Similarly, a third of the total phosphorus was lost in seven years. The organic phosphorus content of the soil under bananas and grass treatments was considered to be a rough approximation of its original status in the soil. By this standard, Anderson estimated that 50 percent of the nutrient was lost under maize cropping and 75 percent under coffee and elephant grass. A similar picture has emerged in South America. In the southern Sierras of Peru deterioration of the land has resulted in a major agricultural decline; in more densely settled areas of Peru and Bolivia, such as the Lake Titicaca Basin, small farms of 2½ ha are frequently found, which cannot support a family under the primitive farming methods practiced. The soil is exploited, erosion occurs, until finally the farm is abandoned and the family emigrates (Eckholm 1976).

In the drier climates of the tropics, control of runoff and soil erosion adds a new dimension to soil productivity. Following several years of research, Krantz et al. (1978), at the International Crops Re-

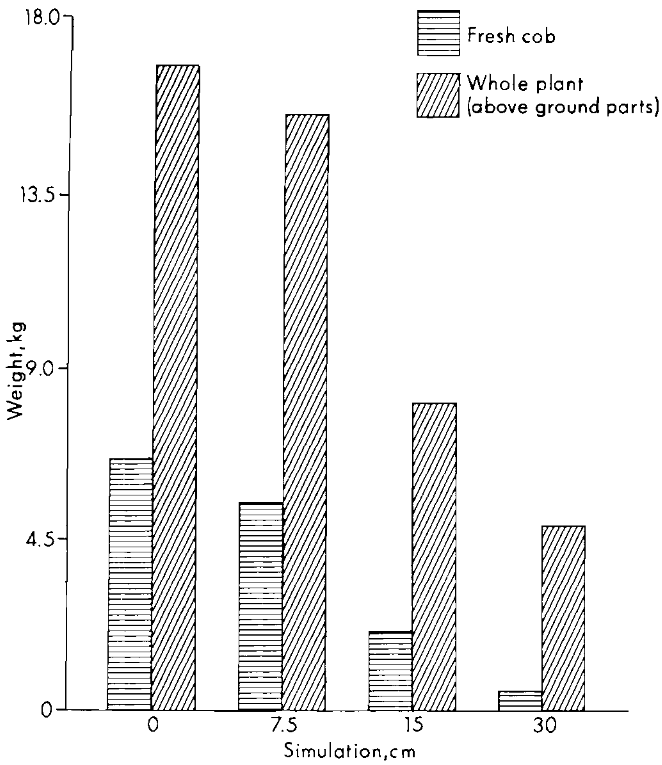


Figure 16. Effects of simulated erosion on yields of maize on a cobbly soil, Malaysia. (Huat 1974)

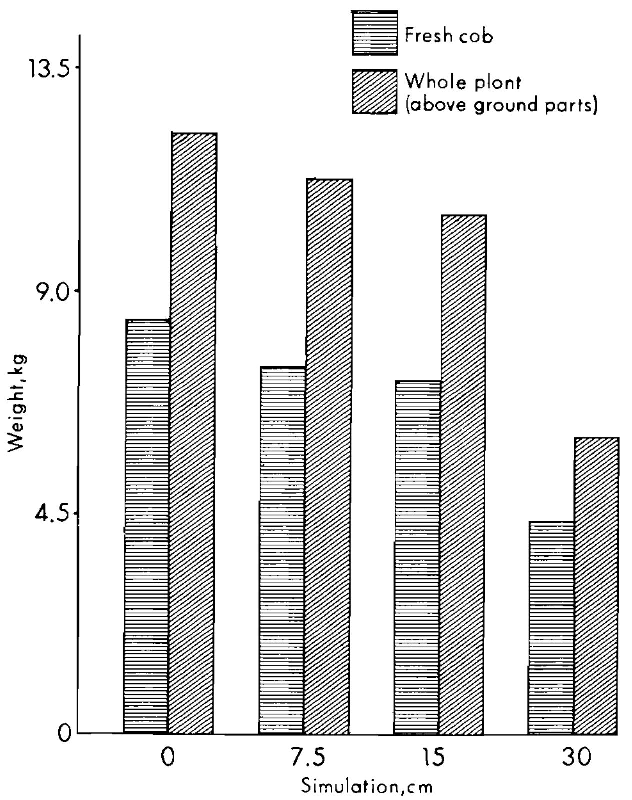


Figure 17. Effects of simulated erosion on yield of maize on a deep soil, Malaysia. (Siew and Fatt 1976)

search Institute for the Semiarid Tropics (ICRISAT), showed that enhancing the water supply available for crop use is instrumental in permitting more frequent cropping particularly of Vertisols. For shallow Vertisols, characterized by little capacity for water storage in the soil profile, the greater runoff in the early rainy (monsoon) season was collected and stored for supplemental "life-saving" irrigations during breaks in the monsoon. Deep Vertisols, on the other hand, generate little runoff during the early monsoon, because they are characterized by high capacity for water storage in their heavy-textured, deep profiles and by surface cracking that enhances high water intakes. By timely tillage during the dry season, dry planting of certain crops, and improved seedbed-preparation techniques (and optional irrigation applications), these soils successfully supported two crops in most years

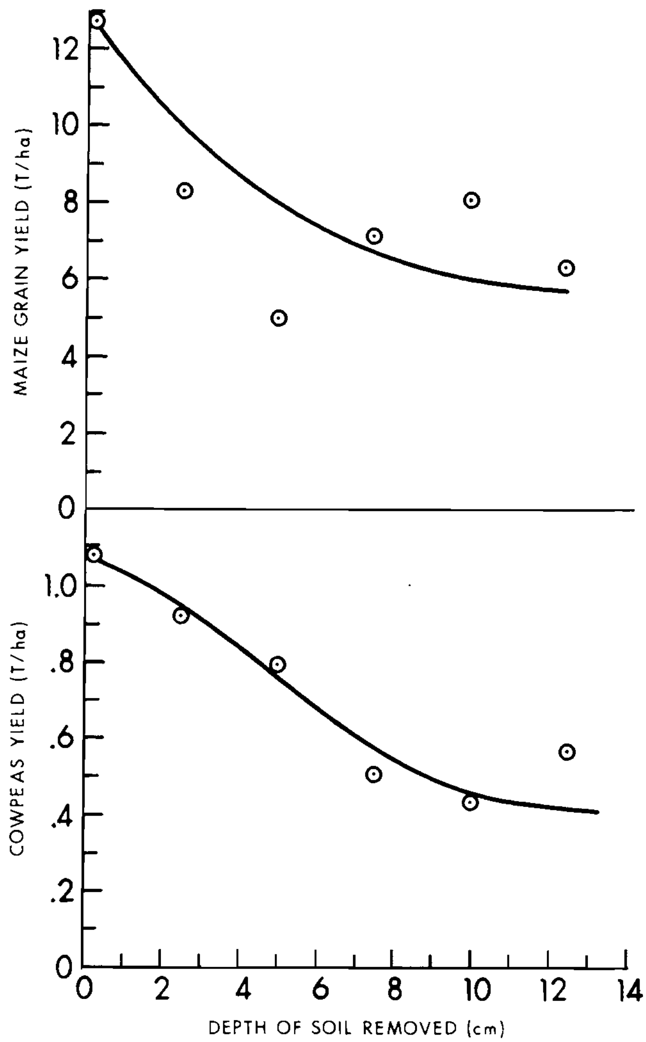


Figure 18. Effect of surface soil removal on grain yield of cowpeas and maize on Alfisols. (Lal 1976*d*)

Table 25. Effect of depth of soil removed on root development

Depth of soil removed (cm)	Maize					Cowpeas				
	root number	average length (cm)	maximum depth (cm)	lateral spread (cm)	dry weight (g/plant)	root number	average length (cm)	maximum depth (cm)	lateral spread (cm)	dry weight (g/plant)
0	5.1	21.4	25	55	5.07	15	10.7	27	29	0.26
2.5	24	19.8	18	40	1.24	10	7.4	17	10	0.11
5.0	24	15.3	13	50	1.03	10	9.1	25	12	0.11
7.5	20	18.1	14	40	0.71	9	8.2	30	11	0.11
10.0	22	13.2	14	35	0.42	8	8.1	24	12	0.06
12.5	21	15.0	11	35	0.67	9	6.7	12	7	0.05

Source: Lal 1976d.

—in contrast to the traditional single crop during the postrainy season. Clearly, the double cropping resulted in better erosion control during the rainy season, with 5 to 7 times less erosion than on traditional fallow. The ICRISAT Farming Systems Staff (1977) demonstrated impressive benefits to the yields of maize, chickpeas, and pigeon peas as a result of improved soil and water conservation practices.

Soil erosion-productivity interrelationships are cyclic in nature. While increased soil loss is cause for declining soil productivity, maintenance of soil productivity is, in turn, essential for supporting healthy stands of vegetation to reduce or eliminate soil loss (Fig. 19). This delicate equilibrium necessitates careful selection of soil conservation practices on farms with low capital and energy inputs (Shaxon 1981*a*).

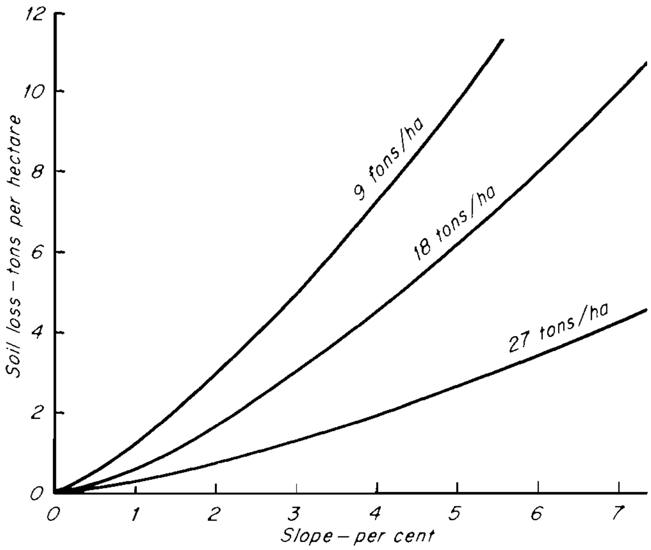


Figure 19. Relationship of three levels of production of maize to soil loss and slope. (Hudson 1971)

Productivity Changes Associated with Sediment Deposition

Throughout history, observations have recorded the benefits to soil productivity of irrigation or flooding with silt-laden (presumably nutrient-rich) river water. Ancient Egyptian agriculture, which supported a renowned civilization, is frequently cited as benefitting from basin irrigation with Nile waters that carry large sediment concentrations during the flood months (see chap. 2). Indeed, there is concern that the decline in sediment load as a result of deposition behind the Aswan High Dam may, among other effects, produce a decline in soil productivity and therefore necessitate increased use of fertilizers in Egypt (Council of Soil and Water Resources Research 1977). In contrast, Uehara (1974) discounted the importance of the benefits from silt deposition when considering Mekong River sediments.

A lesser known but seriously damaging impact of the deposition of erosional sediments is the burial by them of productive soils and crops when runoff from poorly protected uplands floods low-lying lands. Figure 20 shows an example of this problem, observed by El-Swaify in Thailand. While it may at first impression be assumed that the loss in soil productivity is temporary, this frequently is not the case. The buried crop may represent a serious economic blow, and repeated occurrence a lifetime disaster, to the subsistence farmer. Furthermore, when erosion from uplands is so severe that subsoils comprise the major source of sediment, the quality of resulting deposits will be diminished. Regardless of nutrient status, the physical makeup of the deposits is frequently not favorable for root proliferation without major improvements in "soil" structure. A documented example of detrimental burial of pro-

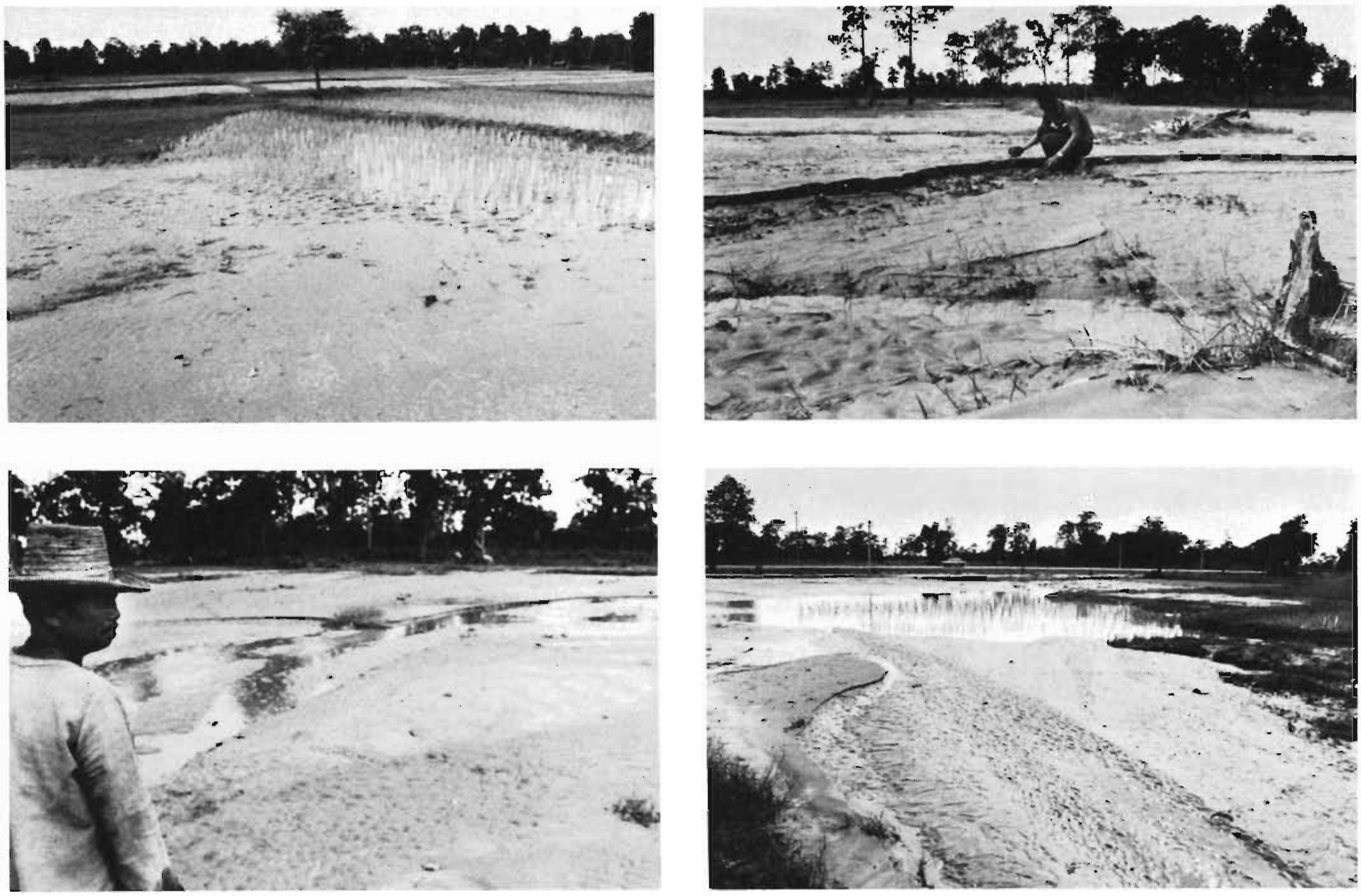


Figure 20. Examples of cropland burial by erosional sediments (rice fields, Northeast Thailand, August 1978). ***Photos: S. A. El-Swaify.***

ductive soil was given by Christiansson (1972). He presented the results of intense sheet and widespread gully erosion on a 34-km^2 catchment near Singida, Tanzania. When the steeper (6°–8°) upper slopes eroded, sometimes to bedrock, and the material was deposited on lower slopes, "this created a serious practical problem as the best cultivation and grazing areas in the valley bottoms were gradually covered by infertile sandy sediments."

FLOOD HAZARDS OF RAINFALL EROSION IN THE TROPICS

Most major human settlements are located adjacent to rivers, which offer obvious benefits such as easy water transportation, abundant rich alluvium for farming, flat land for construction of homes and factories, and immediately accessible water for irrigation, drinking, and industrial use. Egypt has been called "the gift of the Nile" because of its agriculture on the flood plain (chap. 2). However, other places, with water harnessing problems, are less fortunate as they experience periodic disasters from seasonal flooding. Some documented information from different continents is presented below, although it is stressed that the topic of floods and associated hazards has been dealt with in much more detail in specialized references, to which the interested reader should refer (WMO 1970; IAHS 1974).

Classic cases of flooding and associated soil erosion, particularly in East Africa, were presented in chapter 2. In Tanzania, Temple (1972*a*) wrote that "severe short duration flash floods of high sediment content were causing considerable damage." This flooding and silting was estimated to have cost Morogoro township £24,000 in damages over a ten-year period. Rapp, Axelsson, et al. (1972) described damage from a flash flood in 1961, in which 1100 tons of sediment were removed from the township at a cost of £1000. They noted that these deposits were most probably those damaging streets and houses directly and that the total quantity of sediment deposited was likely much higher. Related hydrological studies indicate that devegetation in the Uluguru Mountains has led to reduced water infiltration into soils and consequently higher rates of runoff after rainfall. The reduced infiltration was probably a direct result of soil structure degradation and surface sealing by detached particles. Available information and scarce quantitative data on flood hazards give credence to the view that occasional catastrophic storms every few years cause the major share of erosion damage. At Lyamungu in one year (1937) out of four, runoff losses ranged as high as 26 percent of annual precipitation. Individual storm losses were sometimes excessive due to high antecedent soil moisture and the unfavorable rain distribution pattern within the storm (Temple 1972*a*).

The impact of erosion on hydrology is demonstrated within the Ulugurus and is clearly reflected in one watershed outlet, the Ngerengere River. According to Little (1963), cited by Temple (1972*a*), differences between wet season high flow rates and dry season low flow rates were widening. As a result, the frequency of complete drying up of the river increased, with flow nearly ceasing in the years 1930, 1934, 1943, 1949, 1953, 1955, 1958, and 1960. Temple stated that as a result of this fluctuation, a sisal plantation along the river was forced to halt irrigation for a period of two months; first in 1960 and again in 1966. The cost of an alternate water-supply system for that plantation alone was put at £260,000.

As land use for cultivation and grazing intensified in the late 1960s and as conservation measures were most widely ignored, the Uluguru Mountains were for the first time afflicted with landslides. Large sections of the hillsides slipped downslope, even after rains of moderate intensity. Resultant damage included loss of cultivated land, both from topsoil stripping and from burial; property damage including collapse of buildings and breaching or filling of engineering earthworks; covering or undermining of roads and culverts; crushing of timber; loss of human life; and loss of cattle. A "catalogue" of damages that resulted from the storm of 23 February 1970 was given by Temple and Rapp (1972). Without considering the economic impact of ruined land and lost fertility, the damage from this storm was estimated to be $90,000, affecting 1600 homesteads or 14 percent of those in the area.

The region above 2300 meters (7500 feet) elevation in the Drakensberg Mountains of southern Africa has been identified as susceptible to a peculiarly dangerous form of erosion (Jacot-Guillarmod 1969; Van Zinderen-Bakker and Werger 1974). Extensive bogs and marshy sponges play a vital role in the ecology of these high altitude regions. Jacot-Guillarmod indicated that these bogs are of the utmost importance to the water economy of southern Africa, as they are the sources of so many rivers (the Orange, the Tugela, and the Wilge) and regulate the flow of the extremely high rainfall [from 1250 to 2000 mm annually] in this mountain area. Livestock grazing, diamond mining, and mining support activities have already damaged some bogs and threaten all remaining ones with future destruction. The severe climate allows only slow vegetative recovery, but forces soil erosion at a rapid pace. Water erosion is most common, but in some areas desiccation of the soil followed devegetation and wind erosion resulted. From the eroded bogs (in some places completely washed away, with only bare rock remaining) the regulated and filtered supply of water to streams has ceased. Higher sediment content, with flood damage in the wet season and more intense drought in the dry season, has occurred on a small scale, and threatens the whole system. The economic impact on the lower regions of southern Africa will undoubtedly be disastrous if these unique bogs are extensively damaged.

In China, there are records of floods that have caused more than a million deaths at a time. In recent years, hundreds of thousands of people have died or been left homeless following floods in India, Bangladesh, Pakistan, Korea, and China and their sources of livelihood have been severely damaged (Chorley 1969). Bangladesh is an example of those areas of the world that are particularly vulnerable to flooding. The low topography, vast catchment areas of rivers, and a monsoon climate combine to make this a flood-prone area (Ralph 1975). In Pakistan, the hazardous flood season peaks during June to September. For example, Moazzam (1971) documented a storm from 1 to 6 July 1959 that brought a flood that killed 30 persons and destroyed food and cattle. In India, damage from floods is estimated to produce material losses of U.S. $138 million annually. In addition, an average of 700 human lives and 40,000 cattle are lost annually from flooding (Kulandaiswamy et al. 1973). The principal rivers of the Punjab—the Sutlej, the Beas, the Ravi, and the Yamuna—are particularly prone to flooding. A record disastrous flood occurred in the Punjab in October 1955, in which 4000–5000 people were lost from drowning, being washed away by floodwaters or bitten by aquatic poisonous snakes; loss of cattle was in the thousands as well (Uppal and Sehgal 1956). A short intense rainstorm in August 1960 resulted in the loss of 103 persons as well as 600 cattle. In October 1968 landslides from prolonged heavy rains made a debris barrier across the river Teesta, resulting in the formation of a temporary lake. When the barrier broke a torrent of water caused heavy losses of human life and property and left a heavy deposit of silt after the flood passed. Similarly, in July 1970, water backed up on the Anaknanda River and rose 15 m above the road, leaving village residents engulfed in the flood (Singh et al. 1974). The authors noted that the river was completely choked with silt for its first 16 km. An impressive illustration of damaging siltation associated with flooding was reported by Lal and Banerji (1974). They noted that, because of excessive grazing and quarrying, the Kalagarh Bridge near Dehra Dun, which originally was 36.6 m above the river bed, now has a clearance of only 0.6 m. Burns (1947) noted that when a storm breaks in Sri Lanka, as at the beginning of each monsoon, there are usually several days of heavy rain before the deluge comes. Upon arrival of the deluge, flooding becomes a near certainty as the early rains are generally sufficient to fill the rivers and adjacent areas. As early as 1894 the Kelani Ganga River was silting up rapidly; although navigable at that time, the river no longer is (de Rosayro 1947).

In west Malaysia, flooding is a frequent, serious problem. Roads and rail lines to the northeast are often cut; the East Coast trunk road from Kota Baharu to Johor Baharu faces the prospect of floods for years to come. Great losses of crops, timber, and property occurred during the January 1971 floods (Leigh and Low 1973). In January 1967, devastating floods occurred in the states of Kelantan, Trengganu, and Perak in west Malaysia. Many lives were lost, livestock and agricultural crops destroyed, and considerable losses occurred to property, communication lines, and so on (Tan Hoe Tim 1971). The flood hazards in many locations have been caused directly by forest destruction or replacement with other land uses. For example, it has been found that forest vegetation intercepted 36 percent of the total precipitation in the Sungai Lui catchment, Selangor (Low 1972) and also Sarawak where the forest is mixed Dipterocarp (Brunig 1970). In contrast, an experiment performed on a rubber plantation showed that only 14.7 percent of the total rainfall was intercepted (Teoh 1971).

Heavy rains on 23–24 October 1967 produced flash floods in the Pakokku and Monywa districts of central Burma, washing away thousands of homes, with the loss of approximately 200 human lives. Substantial crop failures resulted from inundation and more than 100 cattle were lost (Htay 1971). Severe flooding of the Mekong River basin in August 1978 caused the loss of 30 lives in Laos with widespread destruction of the rice crop.[3] In Thailand, vast land areas are subject to annual flooding during the peak of the monsoon season, with many crop losses as well as isolation of small, seldom self-sufficient, villages and towns. Flooding has also been a problem in Java for decades. The basin area of the Cimanuk River is especially prone to damage. Even as early as 1947 the town of Indramayu was flooded for 2 months. In 1957, 15,000 ha of rice fields *(sawahs)* were damaged. After the invasion of west Java by the Japanese during World War II, the local people stripped the forest and converted the land into dry cultivated fields. Continual sedimentation of the Cimanuk River resulted and irrigation channels have silted up from lack of maintenance. Stripping of only 5 percent of the forests on the mountain slopes has resulted in a 30 to 70 percent increase in runoff (Partosedono 1974). Devastating floods are also common in the Philippines. In 1972, central Luzon and parts of southern Luzon were hit by floods that destroyed bridges, public buildings, roads and other infrastructures to a value of more than 2 billion pesos; another 891.6 million pesos had to be spent in rehabilitation and repair (Serrano and Suan 1976). Rivers producing the most severe floods in this country are the Pasig, the Cagayan, and the Cotabato, which have damaged property and agricultural land and even taken human lives (Gulcur 1964).

Even in Hawaii, floods occur somewhere in the islands every year. Here it is the southwest or *kona* storms of irregular occurrence that create flood problems. The high volumes of rain that fall cause infiltration rates in the mountains to be exceeded, resulting in disastrous floods on the populated coastal plains. One such flood occurred on Oahu in November 1954, and damaged over 31,000 acres of cropland; a loss of 840,000 Tm of soil or 8000 ha-cm resulted (Christ 1960). The floods of March-to-May 1963 were unusually severe, resulting in four deaths and heavy damage to homes, highways, and other facilities. Fifteen cm fell in 3 hours in leeward Oahu

3. Sombath Somphone, Department of Agronomy and Soil Science, University of Hawaii. Personal communication, September 1978.

and resulted in the drowning of a child (Vaudrey 1963). Flash flooding is frequent. Such floods on Kauai and Oahu on 19 April 1974 took 5 lives, and resulted in $3.9 million worth of property damage (Schroeder 1976).

In the Cauca region of Colombia landslides occur so regularly that "socially important slides occur every few months" (Eckholm 1976). A recent slide dammed the Yumbo River and caused death in the town of Yumbo. Sediment deposits from recent deforestation in watersheds regularly block the Cali and Canaveralejo rivers and cause major flooding in the city of Cali (Eckholm 1976). Furthermore, the deteriorating mountain environments are bringing destruction to towns throughout the Andes. For example in Venezuela, fertile lands south of Lake Maracaibo are annually being flooded and badly affected by the thousands of tons of detritus deposited by the Catatumbo, Esculanti, Chama, Motatan, and Carache rivers (Eckholm 1976). As long ago as 1951, blocking of rivers with sediment caused floods and formation of marshes (Prieto Bolivar 1951). Heavy rains during mid-March 1969, in the state of Alagoas, Brazil, led to disastrous floods; the people were taken unawares, as normally floods occur in June; and 242 were killed. The Mundau River rose 5 meters above its normal level inundating the cities of Uniao dos Palmares, Sao José da Laje, Braquinha, Murici, Rocha Cavalcanti, and others. More than 8000 people were left homeless (Ghose 1971).

These represent only some of the accounts of flood damage that have been documented in published form. It would be safe to assume that the magnitude of the problem far exceeds the cases indicated here. For more comprehensive documentation, see such specialized publications as WMO (1970), IAHS (1974), and reports of similar agencies.

SEDIMENTATION AND USEFULNESS OF RESERVOIRS AND WATERWAYS

Pollution was one of the buzzwords of the seventies. However, it is not generally known that "excess sediment is the major form of human-caused water pollution in the world today and exacts a heavier cost . . . possibly more than all other pollutants combined" (Eckholm 1976). The Anchicaya Dam in Colombia was predicted to have a long life upon its design in 1947 and subsequent completion in 1957. Less than two years later, sediment had reduced its capacity by nearly one quarter (Eckholm 1976). Even in the United States, the acknowledged leader in the fight against soil erosion, it is estimated that three quarters of a billion cubic yards of sediment are dredged from our waterways annually. In other words, the storage capacity of artificial reservoirs in the United States is being reduced at the rate of 1 million acre-feet per year (Bagley 1973). An older survey of 95 of the largest reservoirs in the United States indicated that 40 percent of them will be filled with silt in fifty years and another 30 percent in sixty years (Bishan 1957). A recent study of northern Californian reservoirs indicated that roads along streamsides contributed 6.9 times more sedimentation than roads located on slopes or ridges. Current wildfires and old fires increased sediment deposition in reservoirs by 100 percent and 55 percent, respectively (Anderson 1975).

The sediment carried by peak flood flows in the Nile River formerly served to deposit an estimated 1 mm of silt per year to its flood plains and the narrow strip of land alongside the river. Today, this annual sediment load of 132 million tons is deposited along the watercourse and in the reservoir behind the High Dam at Aswan, Egypt (Shalash 1977). For all practical purposes, river transport of this sediment has been eliminated below the High Dam. As indicated earlier in this chapter, lack of sediment in irrigation water may affect the productivity of soils in lower Egypt. However, sedimentation behind the High Dam has two other major effects. First, the life expectancy of the dam is now estimated to be less than 200 years. The continual reduction in storage capacity will be detrimental to irrigation schemes in the country, a serious problem since Egyptian agriculture is nearly 100 percent dependent on irrigation. Second, as reported by Soliman (1974), the scouring of river banks below the dam by silt-deficient water poses stability problems for lands adjacent to the river. However, as a side benefit, Soliman indicated that certain islands south of Cairo can now be settled, provided revetments are installed.

The problem of scouring is also illustrated by a study of the discharge sediment load characteristics of the Rufiji river basin, adjacent to the Uluguru Mountains of East Africa (Temple and Sundberg 1972). The basin is approximately 40 percent woodland; 32 percent woodland-bush, intermediate or wooded grassland with a little forest; and some settled cultivated area. The source of the sediments, whether from geological erosion or from human-induced accelerated erosion was not mentioned by the authors. They stated that inducing deposition of this sediment behind a river dam would cause bank erosion downstream. This in turn would damage engineering structures, bridges, water intake, and so on. In addition, interruption of the natural cycle of silt and water deposition on the flood plain occurs, thus reducing fertility of the soils. The authors were also concerned about the erosion of valuable sand deposits from the river delta. Although Temple and Sundberg provided no data on the effects on the basin's economy, they indicated that costs of road and bridge reconstruction, of irrigation and fertilization of the flood-plain soils, and of exploiting alternate sand supplies would be necessary. In the same region of Tanzania, the Matumbulu reservoir accumulated sediment during the period of 1960–1971 at the rate of 13,200 m^3 per year for a total of 119,000 m^3. The expected life of the reservoir was therefore, only thirty years. Also in Tanzania, sediments from nearby eroded areas were reported as continually filling the Kisongo Reservoir, which was built in 1960 to increase the cattle-carrying capacity of the range by supplying water for stock (Murray-Rust 1972). Sedimentation reduced the reservoir's capacity at a rate of 3.3 percent annually from 1960 to 1969, and accelerated to 4.8 percent per annum after 1970. A glance at diminishing storage capacity shows that reservoir capacity changed as follows:

Date	Total capacity	Surplus capacity
1960	121,000 m^3	66,000 m^3
1969	83,600	34,000
1971	71,700	22,500
1975	47,900	0

At present rates, the reservoir will be completely silted by 1983, but its useful life of only 15 years ended in 1975. According to Temple and Murray-Rust (1972), the net result of this water development failure is that "carrying capacity of land will drop to a lower level than before the reservoir was completed: due to the drop [through erosion] in available grazing area." As indicated by Rapp, Murray-Rust, et al. (1972), this situation is common to many similar projects in East Africa. The reader is reminded of additional data on reservoir siltation presented in Table 6 (chap. 2).

In Pangasinan, the Philippines, sedimentation resulting from a 1975 flood was so heavy in some agricultural areas that bulldozers had to scrape away a one-meter-thick layer of sediment that came from the denuded mountains (Costes 1975, cited by Serrano and Suan 1976). Almost one fourth of the Cagayan River watershed and the Agno and Pampanga river basins are badly eroded, giving rise to serious siltation. The rate of siltation in the Ambuklao Dam is 2.45 million m^3/yr, a quantity that would require continual use of 47 truckloads per hour at 6 cubic meters per truckload for removal. As a result, the expected lifespan of this dam has been reduced from 62 to 32 years (Weidelt 1975). Other watersheds in the Philippines with critical problems are the Panay-Jalaud River basin, the Bicol watershed, the Allah River watershed in Zamboanga, and the Leyte and Buhisan watersheds in Cebu. Already these are inefficient as sources of irrigation, hydroelectric power, and potable water (Gulcur 1971, cited by Serrano and Suan 1976). The problem of the Buhisan watershed in Cebu is particularly acute. The dam is almost filled with sediment and its usefulness is almost eliminated. Similarly, the Pantagangan Dam which impounds one of the largest artificial lakes in Southeast Asia, is threatened with a shortened life from accelerating sedimentation (PCARR 1977).

In Pakistan, soil erosion and deposition have decreased the life expectancy of the $600-million Mangla Reservoir, planned to last 100 years or more, to 57 years or less (Szechowycz and Qureshi 1973). The Gobindsager Reservoir in India, with a life expectancy originally estimated at 600 years, is likely to be completely silted up in 150 years. The artificial Sukhna Lake at Chandigarh has lost 50 percent of its storage capacity in 13 years (Murphy and Shankaranarayana 1977). Additional data on this prob-

Table 26. Data on siltation in selected reservoirs in India

Reservoir	Annual rate of siltation ($10^6 m^3$) Assumed	Observed
Bhakra (Punjab)	28.4	41.6
Panchet (DVC, Bihar)	2.5	11.8
Tungabhadra (Karnataka)	12.1	50.6
Nizam Sugar (Andhra Pradesh)	0.66	10.8
Ukai (Gujarat)	9.2	26.8

Source: Patnaik 1975.

lem are presented in Table 26. It is of interest to note that designers' estimates of siltation rates have always underestimated observed rates. However, it is difficult to determine whether this is a result of designer optimism or increases in sedimentation rates (resulting from more concentrated human activity in the watersheds) after the initial estimates were made.

OTHER ENVIRONMENTAL IMPACTS OF RAINFALL EROSION IN THE TROPICS

The environmental impacts associated with sediment delivery and deposition in bays, estuaries, lakes, and so on are probably no different for the tropics than for other areas. Damage because of sediments and soluble or associated chemical compounds (fertilizer nutrients and pesticides) has been cited as the cause of the drastic changes in marine life within Hawaii's Pearl Harbor and Kaneohe Bay, on the island of Oahu (Bartram 1975). Although the environmental or pollution hazards of sediments are often associated with esthetic considerations that are considered far less important than the impacts discussed earlier in this chapter, they may be sufficient to affect the livelihood of certain populations in developing countries. Eckholm (1976), in discussing pollution of fisheries, cited the concern of some ecologists (Lusigi 1974) that fish production in the East African Great Rift Lakes is threatened by agricultural and industrial pollution. A particularly trying situation is the rapid sedimentation that is destroying fish production in Laguna Lake in the Philippines; over 100,000 families depend on this lake for their livelihood and protein consumption (Gulcur 1964).

These examples indicate that the environmental consequences of pollution by erosional sediments should not be overlooked, even in developing countries. Quantitatively, it has been found that changes in the optical properties of water are much more drastic when contaminated by sediment derived from oxidic soils than from other soils (Ekern 1977 and El-Swaify and Cooley 1980). It is therefore likely that equal amounts of sediment would be more detrimental to the environment if derived from tropical than from temperate soils.

CHAPTER 4
PREDICTABILITY PARAMETERS FOR RAINFALL EROSION IN THE TROPICS

Conditions that give rise to soil erosion by water have been the subject of many qualitative studies (see chap. 2). However, quantitative predictions based on the roles of individual causative parameters have generally originated and been verified in temperate regions, particularly in the eastern United States (Wischmeier and Smith 1978). While such predictions are possible for certain forms of erosion in locations where individual predictive components have been established, they present definite limitations when their use is extended beyond the original locale (Wischmeier 1976*b*). It is therefore instructive to provide both a qualitative account of conditions that generally enhance soil erosion and an assessment of the success of quantitative predictions of rainfall erosion in the tropics. By necessity, much of the information included in both sections was not obtained in the tropics. Fortunately, the principles that underlie the roles of the different causative factors are universally applicable.

CONDITIONS FAVORING HIGH RATES OF SOIL LOSS IN THE TROPICS

It has long been realized that for water erosion to take place, two distinct processes must be set in motion. First is the action (kinetic energy) of water (rainfall and possibly runoff) to separate detachable particles from the soil mass. Second is the transport (by runoff and possibly rainfall) of detached particles from their point of origin to a new destination. It is clear therefore, that the most important causes of water erosion are the characteristics of rainfall, soil, and physical setting of the land. The rainfall must be of sufficient intensity and duration to cause detachment and produce runoff (that is, exceed the soil's infiltration rate). The soil must be susceptible to particle or aggregate detachment and topography must have sufficient slope steepness and length to allow particle migration with runoff. These basic requirements are clearly modified by the absence, presence, and nature of vegetal cover as well as prevailing cultural practices such as land shaping or tillage.

The following is a list, developed from several sources (particularly ARS 1975), of the general conditions that lead to high rates of soil loss by water erosion:

1. High intensity and long duration of rainfall
2. High rates of overland flow from adjacent uplands
3. Poorly structured soils with low infiltration rates
4. Soils that lack coherence between top and subsurface layers (e.g. loose land fill or soils piled during construction activity)
5. Slopes with high or moderate steepness
6. Long slopes
7. Tillage and/or planting in rows directed with, rather than across, prevailing slope
8. Absent or sparse vegetative cover, with insufficient protective organic residue

Historically, though perhaps not always intentionally, humans have devised a variety of practices that reduce erosional losses by exploiting those parameters that lend themselves to management. Thus, when there was a choice, steep slopes were terraced to reduce the steepness and length of slope and to curtail loss of water by runoff; simultaneous clearing of massive areas of forest was avoided; and shifting cultivation was practiced whenever crops provided poor stands inadequate for soil protection. As emphasized earlier, tropical populations have only recently begun to deviate from well-established, wise uses of land resources because of increased population densities and accompanying needs for food and energy. These pressures exemplify socioeconomic factors that are themselves an "erosion determining parameter" which reaches beyond the physical factors responsible for the actual erosion process.

QUANTITATIVE PARAMETERS FOR PREDICTING RAINFALL EROSION IN THE TROPICS

Equations commonly used for predicting soil loss and prescribing erosion control measures were developed primarily in the Corn Belt (Midwest) of the United States. Historical review of steps leading to their development were given by Wischmeier and Smith (1978), Mitchell and Bubenzer (1980), and Moldenhauer and Foster (1981). First, a relationship between soil loss and slope length and steepness was developed by Zingg (1940). Crop cover and conservation practice parameters were added the following year by Smith (1941). In 1946 the Musgrave equation emerged, with the addition of a rainfall parameter (Musgrave 1947). Based on data from over twenty-five years' research, from which the rainfall parameter was modified and the soil susceptibility to erosion (erodibility factor) quantified, the universal soil loss equation (USLE) for predicting sheet and rill erosion was proposed (Wischmeier and Smith 1961, 1965). This equation is now the most widely used model for predicting sheet (interrill) and rill erosion (Wischmeier and Smith 1978). It has the form

$$A = RKLSCP \tag{1}$$

and identifies six parameters (factors) as most influential in rill and interrill soil erosion by water: rainfall erosivity (R), soil erodibility (K), cropping-management (C), erosion control practice (P), and two topographic factors—length of slope (L), and steepness of slope (S). The authors quantified all parameters as "mean annual values" based on statistical analysis of voluminous soil loss data gathered from cropland erosion research stations east of the Rocky Mountains (Wischmeier and Smith 1965). Thus the R (rainfall) factor was defined as the number of erosion-index units associated with a normal year's rain; K as the soil's erosion rate per unit of rainfall erosion-index under unit values of the four remaining factors; L as the ratio of soil loss from the given slope length to that from a standard length of 22.13 m (72.6 ft) on the same soil type and slope gradient; S as a ratio of soil loss from the prevailing field slope gradient to that from a standard 9 percent slope; C as a ratio of soil loss from a field with specified cropping management and cover history to that from a comparable field in fallow condition; and P as a ratio of soil loss from contoured, strip-cropped, or terraced land to that from land under straight row cultivation up-and-down the slope.

The USLE is universal only insofar as it identifies all the parameters that determine the magnitude of soil loss due to rill and interrill (sheet) erosion. It is not useful, nor was it intended, for estimating losses caused by other forms, such as gully erosion (chap. 1). The equation has been used successfully by soil conservation planners in many parts of the United States for nearly two decades. Unfortunately, perhaps because of its name, it has also been misused widely within and outside this country. The developer of the equation recently expressed concern over this matter and reiterated the capabilities and limitations of the equation (Wischmeier 1976*b*). As discussed by other authors (Hudson 1971; El-Swaify and Dangler 1977; Lal 1977*a*), he stated that applying the equation in a new area (such as the tropics) without changing its component values is a misuse. So are applications for predicting soil losses from individual storm events or even specific years rather than from a long-term mean-annual basis, or for estimating sediment yields (e.g. from watershed delivery outlets) rather than erosion losses from original positions at specific field sites. Current research efforts aim to establish an equation that will be capable of estimating soil losses from individual storms, which (as stated above) is a function not intended for the USLE (Foster et al. 1977*a, b*). It is instructive to note here other potential errors associated with the use of the USLE as recommended by Wischmeier and Smith (1965, 1978). The following list is directly quoted from Wischmeier (1976*b*):

> Evaluating the [equation's] factors on too broad a base, such as a single C value for all cropland or all corn land.
>
> Applying C and P values from the handbook [USDA 282] indiscriminately without considering length limits beyond which the practices become ineffective. When a practice breaks down from too much accumulation of runoff, the effective C or P value increases rapidly.
>
> Extrapolating factor relationships far beyond the range of the data from which they were derived. This hazard, always speculative, applies primarily to L and S.
>
> Until research can expand the data, extrapolations of the formulas provide the best information available, but their limitations must be recognized.

Defining slope length incorrectly. The effective slope length is the distance from the point of origin of overland flow to the point where either the slope decreases enough that deposition begins or the runoff water enters a well-defined channel. Thus, a slope length is measured to a well-defined channel and does not include the length of the channel. Neither is a slope length terminated by a pronounced change in gradient or land use unless the runoff is diverted.

Evaluating irregular slopes. The slope-effect chart [in the Handbook] reflects relationships for uniform gradients. A convex slope loses more soil than an equivalent uniform slope, and a concave slope loses less. It is logical and correct to divide appreciably irregular slopes into relatively uniform segments for evaluation, but the segments cannot be treated as independent slopes if one segment receives runoff from another. A method of computing LS for irregular slopes was published [Foster and Wischmeier 1974].

In some earlier publications, factor R, unfortunately, was categorically equated with the local EI value. R should be defined as the rainfall and runoff erosivity. EI generally reflects this combination, but there are two exceptions. First, EI does not reflect the erosive potential of runoff that is not directly associated with rainfall. In the Palouse region of the Northwest, probably 90 percent of the erosion is caused by runoff from thaw and snowmelt. The erosive potential of this runoff must be added to the local EI value to evaluate R. Second, on the Southeast Coastal Plains, computed annual EI values are very high because of the hurricane-associated storms and the slope gradients are quite small. Field observers have suggested that the normally computed EI values seem to overestimate soil loss for this condition. A logical assumption is that this is largely attributable to shielding of the soil surface by excessive ponding of rainfall during the prolonged periods of high intensities. But further study is needed to determine the variables and interactions responsible for the apparent overestimation.

Because it has been applied successfully on the U.S. mainland, the USLE has also received some use in other parts of the world, including tropical regions (Roose 1977*c*; Hurni 1981). However, the equation has yet to be fully tested for applicability in these regions. This is partly due to the rigorous requirement of basing its use on site-specific, long-term (preferably 20 years) data for component parameters. Unfortunately, no alternative comprehensive models are available for the tropics, or indeed elsewhere. Elwell (1977, 1981) proposed a Soil Loss Estimation Model for Southern Africa (SLEMSA) which is a modification of the USLE for simplified application in developing countries. However, this model too requires some long-term data inputs and lacks the verification necessary for wider use. Below we will present available information for quantifying the individual causative factors for erosion in the tropics, whether or not they were intended for use in the USLE. By necessity, information from tropical regions will be contrasted with information from temperate areas, where most of the quantitative relationships originated.

Rainfall and Runoff Erosivity

Rainfall initiates the process of erosion by water whether it produces soil detachment and transport directly by raindrop splash or does so by overland flow. Therefore, it is of interest to examine some rainfall data from the tropics and subtropics (Table 27). For example, areas in the vicinity of Cairo, Egypt and Lima, Peru obviously are not generally subject to water erosion because of their negligible annual rainfalls (28 mm and 41 mm, respectively). Located as they are in the arid tropics or subtropics, these areas are more subject to wind erosion. However, many tropical areas receive more than 2500 mm (100 inches) rainfall per year, and many of them receive substantial rains every month (e.g. Manado, Celebes; Padang, Sumatra; Cairns, Queensland; Belém, Brazil). Others have dry periods of greater or lesser duration (e.g. Sittwe and Rangoon, Burma; Freetown, Sierra Leone; Cochin, India). Consequently, in these latter areas, rainfall is even more intense as it is concentrated within the more or less shorter wet season.

Perhaps nowhere are extremes in rainfall more evident than in Hawaii. In a 5-mile distance from Waikiki Beach to the head of the Manoa Valley on Oahu, annual rainfall ranges from < 250 mm to > 4050 mm. Mt. Waialeale on Kauai is considered the "wettest place on earth" with approximately 12,000 mm rainfall annually. Yet the business district of Honolulu receives about 650 mm yearly. Over 3150 mm of rain fell during March 1942 at Laupahoehoe, Hawaii[1] and 1972 mm was recorded

1. James Thropp, Laupahoehoe Sugar Company, Hawaii. Personal communication, 27 April 1978.

Table 27. Rainfall in selected tropical and subtropical locations

	Number of months with > 76 mm	Mean annual rainfall (mm)
Africa		
Addis Ababa, Ethiopia	5	1260
Bathurst, Gambia	4	1295
Bolobo, Congo	9	1539
Cairo, Egypt	0	28
Douala, Cameroon	10	4039
Freetown, Sierra Leone	8	4430
Mongalla, Sudan	7	998
Pretoria, South Africa	5	658
Yaounde, Cameroon	8	1580
Asia		
Bombay, India	4	2017
Cochin, India	8	2913
Colombo, Sri Lanka	11	2344
Hinatuan, Philippines	12	4305
Hong Kong	7	2162
Karachi, Pakistan	0	196
Kupang, Timor	5	1468
Madras, India	6	1270
Manado, Celebes	12	2657
Mandalay, Burma	5	828
Natrang, South Vietnam	4	1382
Padang, Sumatra	12	4486
Rangoon, Burma	5	2530
Saigon, South Vietnam	7	1984
Sittwe, Burma	7	5179
Australia		
Cairns, Queensland	12	4206
Darwin, Northern Territory	6	1570
Pacific Islands		
Apia, Western Samoa	12	2870
Aranoka, Kiribati	7	1043
Atuona, Marquesas Islands	11	1215
Bora Bora, Society Islands	12	2031
Diloon's Bay, Vanuatu	10	1779
Enewetak, Marshall Islands	7	1470
Guam, Mariana Islands	12	2181
Hilo, Hawaii	12	3470
Honolulu, Hawaii	5	649
Matuku, Fiji	12	1777
Ponape, Caroline Islands	12	4875
Swain's Island, Amer. Samoa	12	2870
Caribbean and Central America		
Catcamus, Honduras	6	1255
Colon, Panama	10	3236
El Recreo, Nicaragua	11	3099
Guadalajara, Mexico	4	894
Havana, Cuba	7	1224
Merida, Mexico	6	925
Port-of-Spain, Trinidad	8	1610
San Jose, Costa Rica	7	1948
Vera Cruz, Mexico	6	1689
South America		
Asuncion, Paraguay	9	1316
Belem, Brazil	12	2770
Caracas, Venezuela	6	863
Georgetown, Guyana	11	2253
Inquisitos, Peru	12	2736
La Paz, Bolivia	0	555
Lima, Peru	0	41
Manaus, Brazil	9	2095
Quito, Ecuador	8	1115
Quixeramobin, Brazil	4	752
Rio de Janeiro, Brazil	8	1162

Sources: Blair and Fite 1965; Lamb 1972; Miller and Thompson 1975; Taylor 1973.

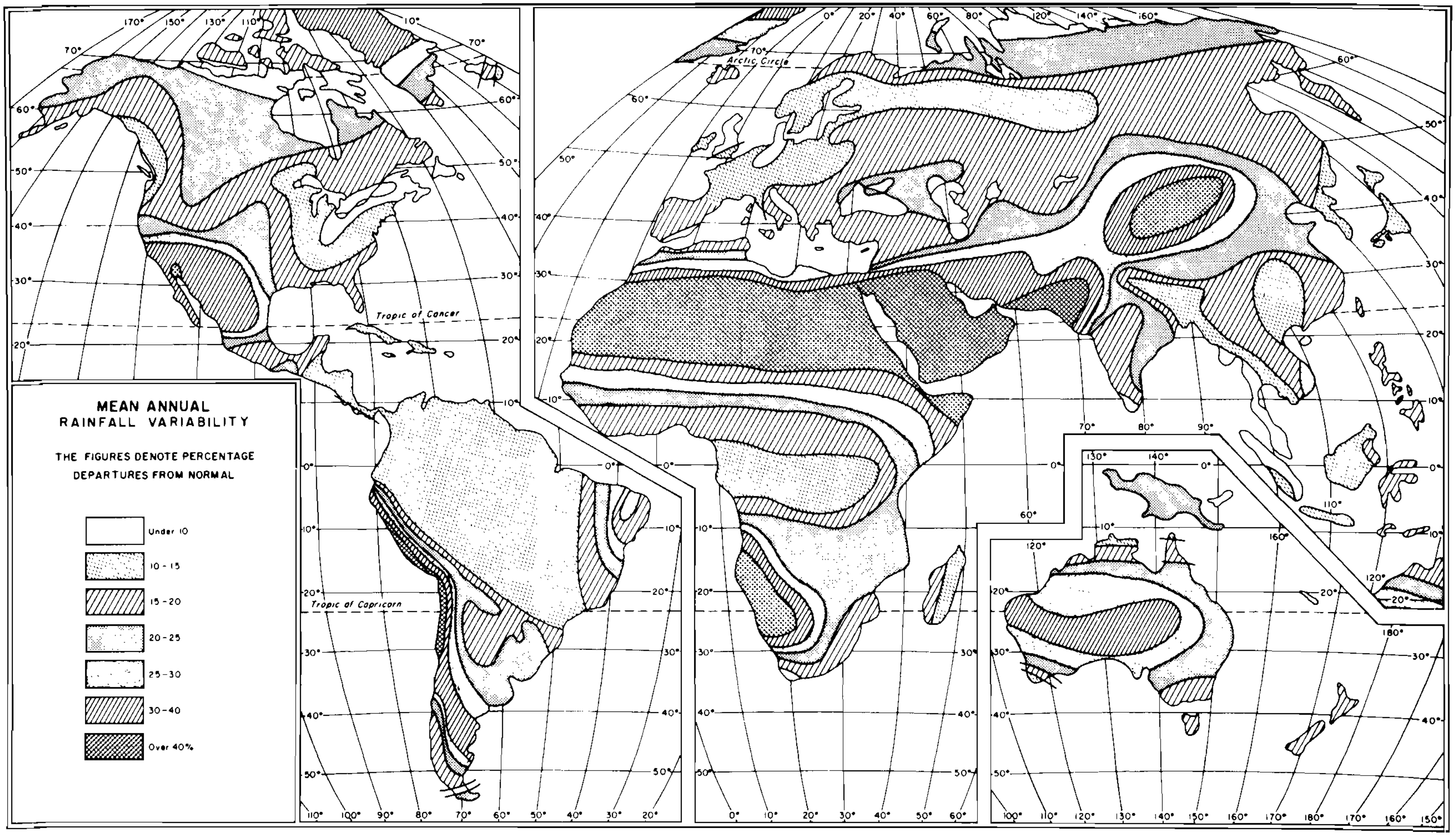
during 7 days in January 1979. Typhoon seasons in the western Pacific bring intense rains (Blair and Fite 1965). Luzon, in the Philippines, has experienced rainfalls of 1000–1250 mm within 24 hours. In Colombo, Sri Lanka, 250 mm of rain fell in 90 minutes (Burns 1947). However, the record 24-hour rain occurred on the island of Réunion at Cilaos in the Indian Ocean with a deluge of 1870 mm (73.6 in).

Although very useful for estimating relative erosion hazards, mean annual rainfall is not directly correlated with soil loss in the tropics. This apparent contradiction is partly due to the extreme variability in mean annual rainfall and seasonal rainfall patterns in given locations (Map 19); storm characteristics differ in different regions, as do other factors affecting the erosion process. For example, it may be recalled that the semiarid tropics are more prone to rainfall erosion than are the undisturbed humid tropics, as a result of the different qualities of vegetative cover (chap. 2; Fig. 7). Futhermore, the seasonal distribution of annual rainfall differs widely from one place to another (Maps 20–23). As expected, the concentration of rainfall in short seasons enhances its effectiveness for inducing erosion. Although the parameter of rainfall most related to erosivity of rain eluded researchers for many years, it has now been established that the characteristics of individual raindrops (number, size distribution, and terminal velocity) are of primary consideration in quantifying rainfall erosivity. Many studies have been made of raindrop size (Laws and Parsons 1943; Hudson 1964*b*) and terminal velocity (Laws 1941; Gunn and Kinzer 1949). Parameters directly related to these characteristics have been tested, with varying degrees of success. These included momentum (Rose 1960), kinetic energy (Mihara 1959) and intensity. Rose (1958) used simulated rainfall to study splash erosion of soils in Uganda. He found momentum per unit area of raindrop to be most closely correlated with soil loss. Hudson (1963) accumulated considerable data in Rhodesia showing that median raindrop diameter increased up to an intensity of 75 to 100 mm/hr but then decreased. Kowal and Kassam (1976) reported that rainfall intensities and median drop sizes are greater in northern Nigeria than in temperate or subtropical climates. Wischmeier and Smith (1958) found as a result of extensive statistical analysis that EI_{30}, the product of the total energy of a rainstorm (E) and the storm's maximum intensity for a 30-minute duration (I_{30}), gave the best correlation with soil loss. Soil losses from erosion stations were linearly correlated with EI_{30} as long as the other 5 factors of the USLE remained constant. To construct an erosivity map based on this index, it is clear that not only must long-term (20 yr) rainfall records be available but also such records must be available on a continuous-recording basis for individual storms. Calculations of storm energy from intensity data have been attempted by various authors (Table 28). The different units for expressing energy and intensity data are also shown in that table. Wischmeier and Smith's (1958) equation is now most widely used for calculating E; I_{30} is derived directly from continuously recorded storm data. Wischmeier and Smith (1978) provided a detailed procedure to accomplish such calculations in both English and metric units. Due to the unavailability of continuously recorded rainfall in many areas, these authors tested various alternatives for estimating the EI_{30} index (Wischmeier and Smith 1962). For the mainland United States, the 2-yr probabilities of 6-hr rainfall (P) were best for making these estimates. The relationship used was

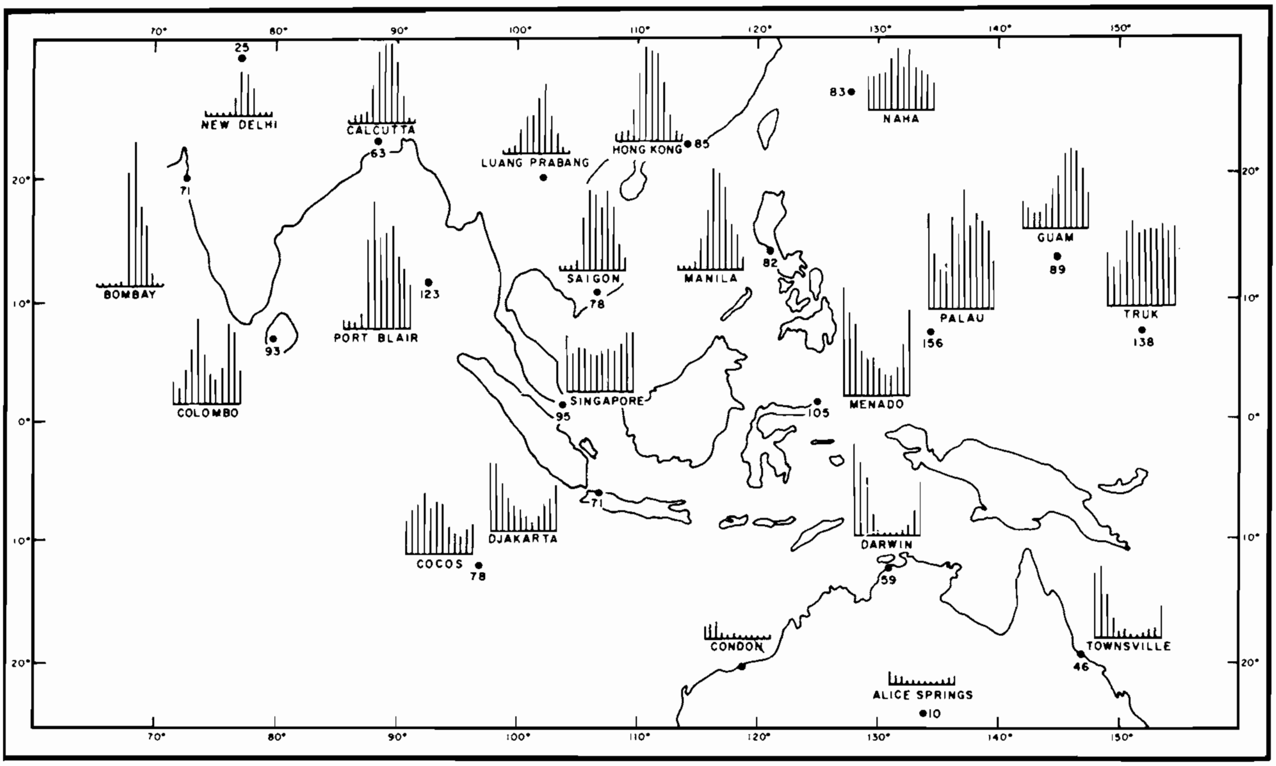
$$EI_{30} = 27.38P^{2.17} \tag{2}$$

Based on this index, an isoerodent map was prepared for croplands of the United States east of the Rocky Mountains (Wischmeier and Smith 1965). Ateshian (1974) added erosivity values for areas west of the Rockies and proposed an analytical approach to estimate the rainfall erosion index. The original isoerodent map was later expanded to cover the western states and modified for the Southeast where the original higher values were found to overestimate soil loss (Wischmeier and Smith 1978). Rainfall index values on the recent map range from < 20 to 550 units. For Hawaii, the product of 5 yr-2 hr and 1 yr-6 hr rainfall was well correlated with EI_{30}. However, the correlative data base for the Hawaii study was so small (only 4 rainfall stations) that further tests of its validity are required. Estimated isoerodent maps for the islands are shown in Map 24. El-Swaify and Cooley (1980, 1981) reported erosivity index values ranging from 139 to 739 in selected locations on Oahu and Hawaii, showing clear voids in these maps.

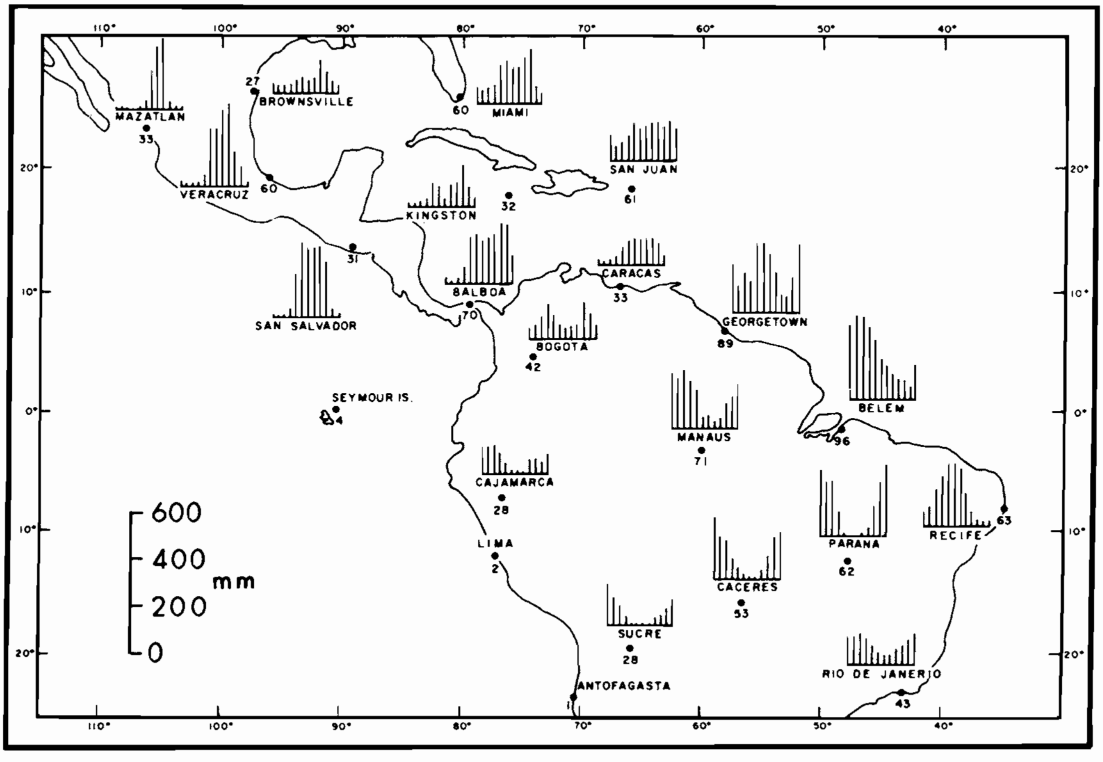
Several other attempts have been made to apply the EI_{30} index or indices closely correlated with it, for mapping rainfall erosivity in the tropics: Bols (1978) prepared a map following a regression analysis between daily rainfall and daily erosivity for 47



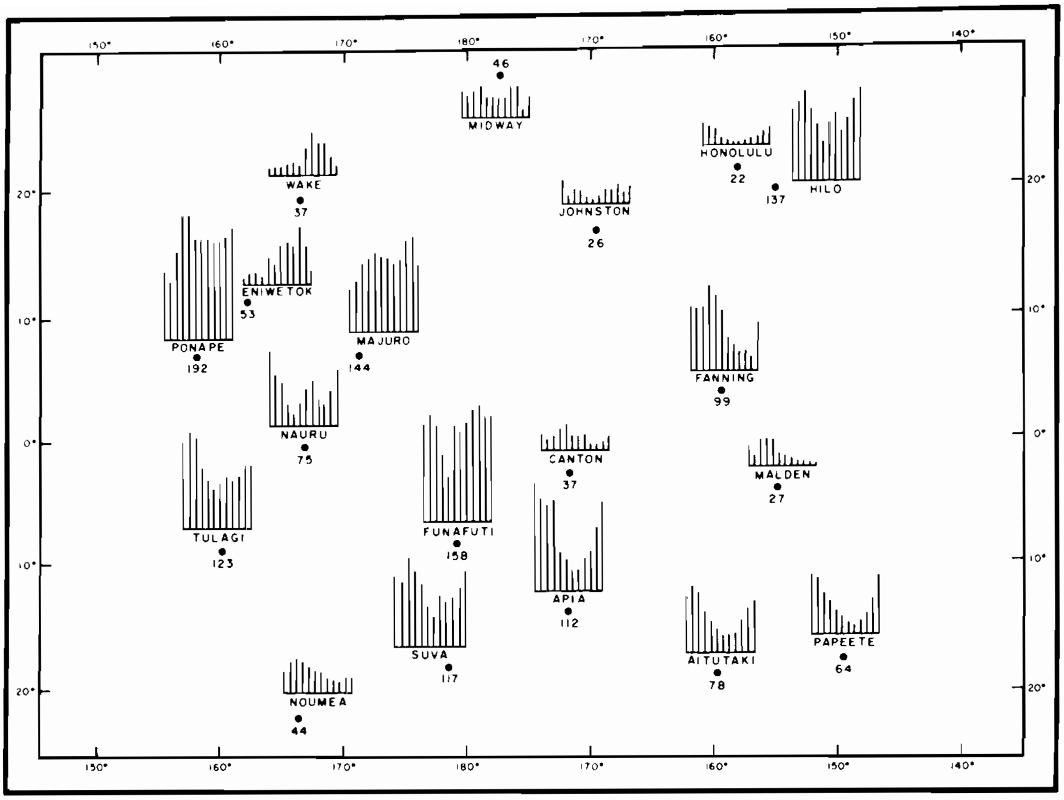
Map 19. Mean annual rainfall variability for the world. See text for explanation. (Atkinson 1971)



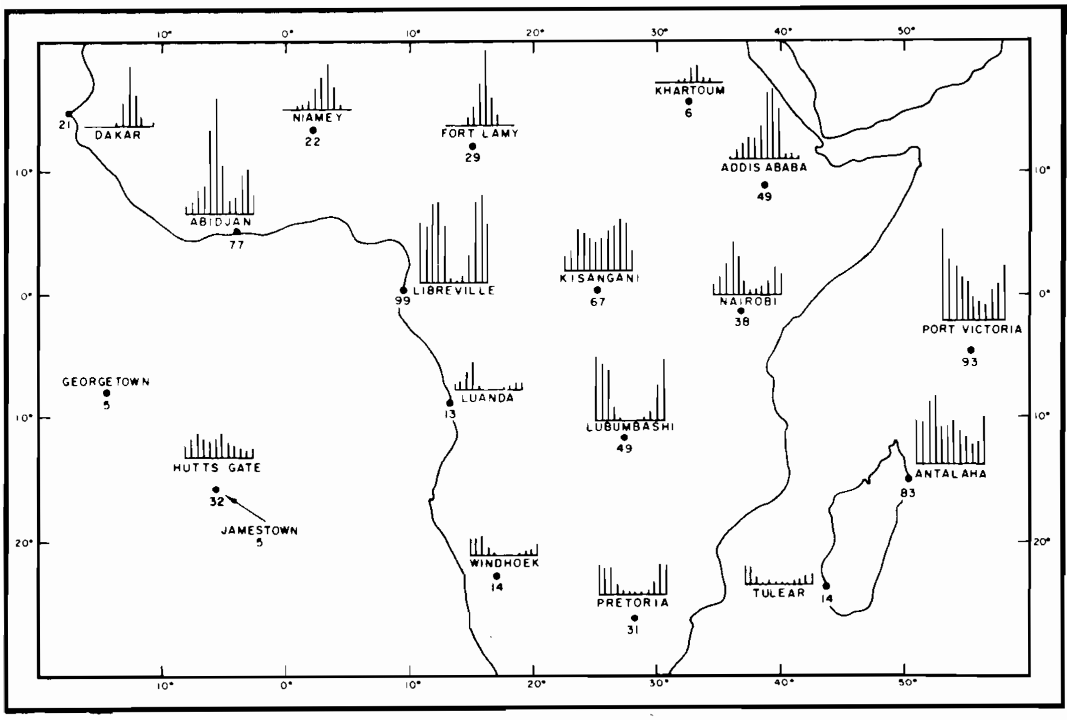
Map 20. Mean monthly rainfall for selected stations in Asia/Australia. Numbers next to place names indicate mean annual rainfall in inches. (Atkinson 1971)



Map 21. Mean monthly rainfall for selected stations in the Americas. Numbers indicate mean annual rainfall in inches. (Atkinson 1971)



Map 22. Mean monthly rainfall for selected stations in the Pacific and Africa. Numbers next to place names indicate mean annual rainfall in inches. (Atkinson 1971)

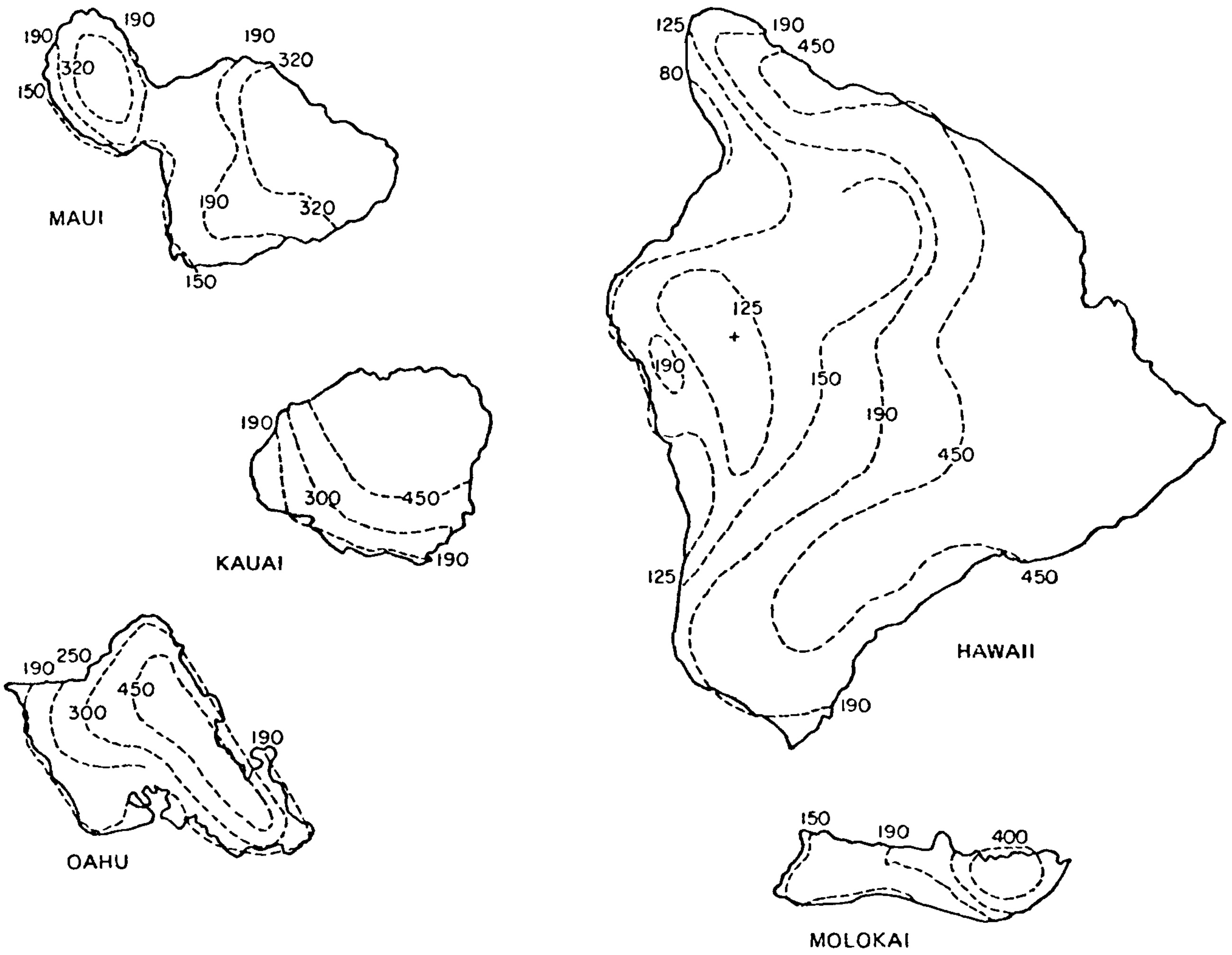


Map 23. Mean monthly rainfall for selected stations in Africa. Numbers indicate mean annual rainfall in inches. (Atkinson 1971)

Table 28. Interrelationships between raindrop size, storm kinetic energy, and intensity, as established by various workers

Location	Climate/Type of precipitation	Intensity range studied	D_{50} versus I	E versus I (Units of E)	E versus I (Units of I)	Reference
Washington DC	Temperate/ Predominantly frontal	0.03 to ≈2 in/hr Limited data 2-4.6 in/hr	$D_{50}=2.23I^{0.182}$	-- --	 $(\frac{in}{hr})$	Laws and Parson (1943)
		0.15-4.6 in/hr Extrapolated to 10 in/hr	--	$E = 916 + 331 \log_{10} I$ $(\frac{ft\ ton}{ac\ in})$	 $(\frac{in}{hr})$	Wischmeier and Smith (1958)
Zimbabwe	Subtropical/ Convective thunderstorms	< 9 in/hr Limited data > 6.5 in/hr	Peak D_{50} of 2.55 mm at I of 3-4 in/hr	$E = 758.52 - \frac{127.51}{I}$ $(\frac{ergs \times 10^3}{cm^2})$	 $(\frac{in}{hr})$	Hudson (1965)
Miami FL	Temperate/ Five types	≈0.1 to ≈9.5 in/hr Limited data > 6 in/hr	--	$E = 8.37\ I - 45.9$ $(\frac{ergs}{cm^2\ sec})$	 $(\frac{mm}{hr})$	Kinnell (1973)
South Central USA	Temperate	< 10 in/hr Limited data > 5 in/hr	$D_{50}=1.63+1.33I - 0.33\ I^2+0.02I^3$	$E = 429.2 + 534.0\ I - 122.5I^2 + 78\ I^3$ $\frac{ft\ ton}{ac\ in}$	 $\frac{in}{hr}$	Carter et al. (1974)
Western Nigeria	Humid tropical/ Convective thunderstorms	Approximately 0.5 - 9.5 in/hr	D_{50} Range: 1.5 to 4.5 mm D_{50} Increases with I	-- --	 --	Aina et al. (1977)

Explanation of symbols: D_{50} is median volume drop diameter; E is kinetic energy per unit volume of rainfall; I is rainfall intensity. Units are reported as published by authors.



Map 24. Estimated average annual values of the rainfall erosion index in the major islands of Hawaii. (Wischmeier and Smith 1978)

rainfall stations in Java and Madura, Indonesia (Map 25); an erosivity map (Map 26) was prepared for the Indian subcontinent (CSWCRTI 1977); Bhatia and Singh (1976) indicated that EI_{30} was best correlated with soil loss for India; and Roose (1977*c*) used metric EI_{30} units to construct a rainfall erosivity map for West and Central Africa (Map 27).

The utility of the EI_{30} as a rainfall erosion index for the tropics has been critically analyzed by many workers. One important basis for criticism is the requirement of elaborate long-term rainfall records, which are not available in many developing countries. Another is the fact that successful use of the EI_{30} in certain temperate regions (such as its place of origin) does not guarantee its success as an index of soil loss in regions with substantially different climates, such as the tropics. The examples provided above, where the EI_{30} has been extended for use in different geographical locations have, by and large, not been justified by actual testing. As will be discussed in chapter 6, this is one of the high-priority research areas for understanding the rainfall erosion process in the tropics.

Approximating the EI_{30} index by well-correlated rainfall probability data may be equally criticized. In contrast to Wischmeier's procedure, many authors have sought a relationship between easily measured rainfall parameters and a rainfall erosivity parameter (Table 29). Good correlations between storm kinetic energy (E) and rainfall amount (A) were reported by Charreau (1969), while relationships between I_{30} and A were not well defined. A relationship defining EI_{30} as a function of A and of I_{30} (Delwaulle 1973) requires rarely accessible I_{30} data. Roose (1977*c*) showed that a relationship between EI_{30} and A alone was valid within a precision of 5 percent in the Niger, Upper Volta, Ivory Coast, Senegal, and Benin areas except where the ocean and mountains influence rainfall. This relationship was used to develop the EI_{30} map (Map 27). To better describe the erosivity of tropical storms, Wilkinson (1975) modified the kinetic energy times maximum 30-minute intensity index (EI_{30}) for the soils and vegetative conditions of Nigeria. In calculating the erosion index, he did not begin the EI_{30} summation for a given storm until runoff occurred, therefore eliminating that portion of rainfall which was accepted by (infiltrated into) the soil. After testing several rainfall parameters in Nigeria against single storm soil loss from bare plots, Lal (1976*c*) found high correlations and insignificant differences between Hudson's KE > 1 (see next paragraph), EI_{30}, rainfall amount (A), maximum rainfall intensity for a minimum duration of 7.5 minutes (I_m), AI_m, and kinetic energy (E). Lal (1976*c*) also indicated that EI_{30} may underestimate the kinetic energy of tropical storms and suggested that the use of AI_m instead may be more advantageous. He was able to estimate this index linearly from rainfall amounts (A) at Ibadan, Nigeria, so eliminating the need for recording rain gauges. However, such simplification cannot be extended to other tropical regions unless a similar correlation can be successfully demonstrated. Furthermore, Lal emphasized the temporary nature of the proposed AI_m index because it is not based on kinetic energy considerations for tropical storms. Aina et al. (1977) discovered that AI_mV, where V is the terminal velocity of the median diameter raindrop, was best correlated with soil loss, whereas Kowal and Kassam (1976) established a relationship between E and A alone. Bailly et al. (1976) noted a good correlation between A and EI_{30}.

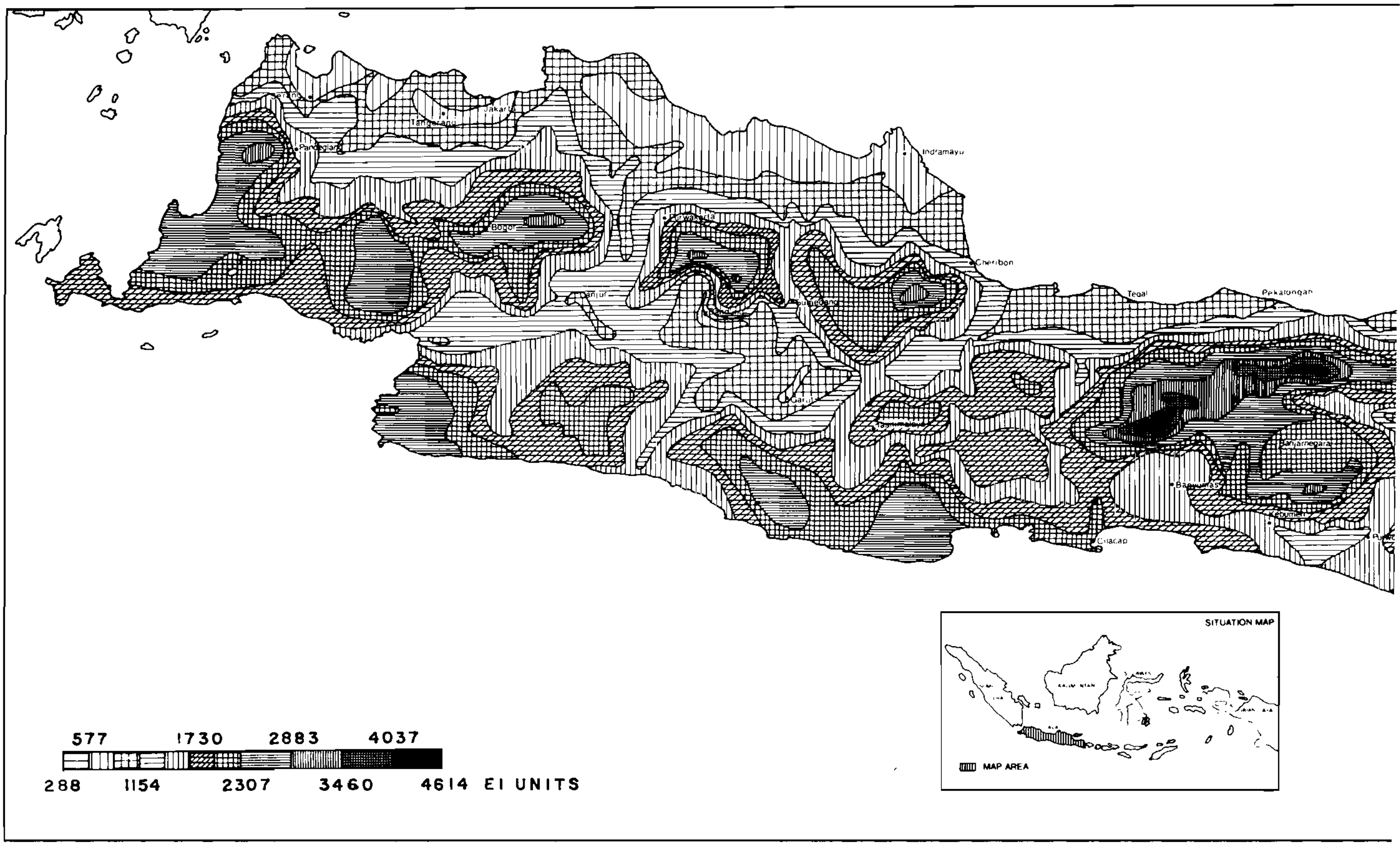
Other significant modifications of EI_{30} have been provided by various authors. Hudson (1971) defined the KE > 1 as the sum of the kinetic energies in storms resulting from intensities greater than 1 in/hr (25 mm/hr). He argued that such an index is more adequate for describing rainfall erosion hazards for tropical soils, which are generally characterized by well-structured profiles and infiltration rates greater than 1 in/hr. It must be noted that Wischmeier's EI_{30} index also omitted those storms of < 0.5 in (12.55 mm) which are separated by 6 hr or more even in the U.S. mainland (unless the maximum 15 min intensity was > 0.95 in/hr). Langbein and Schumm (1958) found that maximum sediment yield occurs in rivers when the annual effective precipitation is between 10 and 14 inches (254–356 mm). Annual rainfall less than 10 inches produced little runoff. The paradoxical decrease of sediment for higher rainfalls is attributed to the increase of vegetative cover. Arnoldus (1977*b*) stated that poor correlations between EI_{30} and soil loss were found in Benin, west Africa. Stocking and Elwell (1973*a*) found that EI_{15}, where I_{15} is the maximum 15-minute intensity, was best correlated with soil loss under limited cover in Zimbabwe. Elwell and Stocking (1973*a*) had found that the total cumulative momentum of the rain in all storms could be used interchangeably with energy without loss of accuracy in the EI relationship. Upon reexamining their data, they found the kinetic energy (KE) for storms with an intensity threshold of 4.3 mm/hr and above to be exponentially related to annual soil loss. Stocking and Elwell (1976) produced a map of mean annual erosivity for Rhodesia using this parameter (Map 28).

For other soils, crop types, and crop stages, Elwell and Stocking (1973*a, b*) found cumulative rainfall momentum above intensities of 2.1 mm/hr to be a better estimation parameter. A subsequent analysis of these data on a daily basis yielded correlations between soil loss and the product of rainfall energy and intensity (Stocking and Elwell 1973*a*). The intensity duration that provided the best correlations varied with the density of crop cover. They also combined soil loss data from grazing trials on a sandveld (Elwell and Stocking 1974) with the earlier data and determined that rainfall quantity parameters were useful for soil loss estimation (Elwell and Stocking 1975).

A distinctly different approach to estimating rainfall erosivity has been devised by Fournier (1960). He was also faced with a lack of recording raingauge data in his attempts to relate suspended sediment loads in African rivers (integrated in a specific degradation parameter in Tm/km^2) to climatic parameters and topography (see later, this chapter, and Fig. 8). He successfully correlated annual specific degradation to a rainfall distribution coefficient C defined as $\frac{p^2}{P}$ where p is mean rainfall for the wettest month of the year and P the mean annual rainfall. His equation for the relationship between sediment yield (D) and the above coefficient is

$$D = K_1 \left(\frac{p^2}{P}\right) - K_2 \qquad (3)$$

with K_1 and K_2 being constants which he identified as important for the distinction between different climatic types (such as semiarid versus humid). Soil erosion is predicted by this equation only insofar as the suspended sediment load of a river is related to a



Map 25. Isoerodent map of Java and Madura. (Bols 1978)

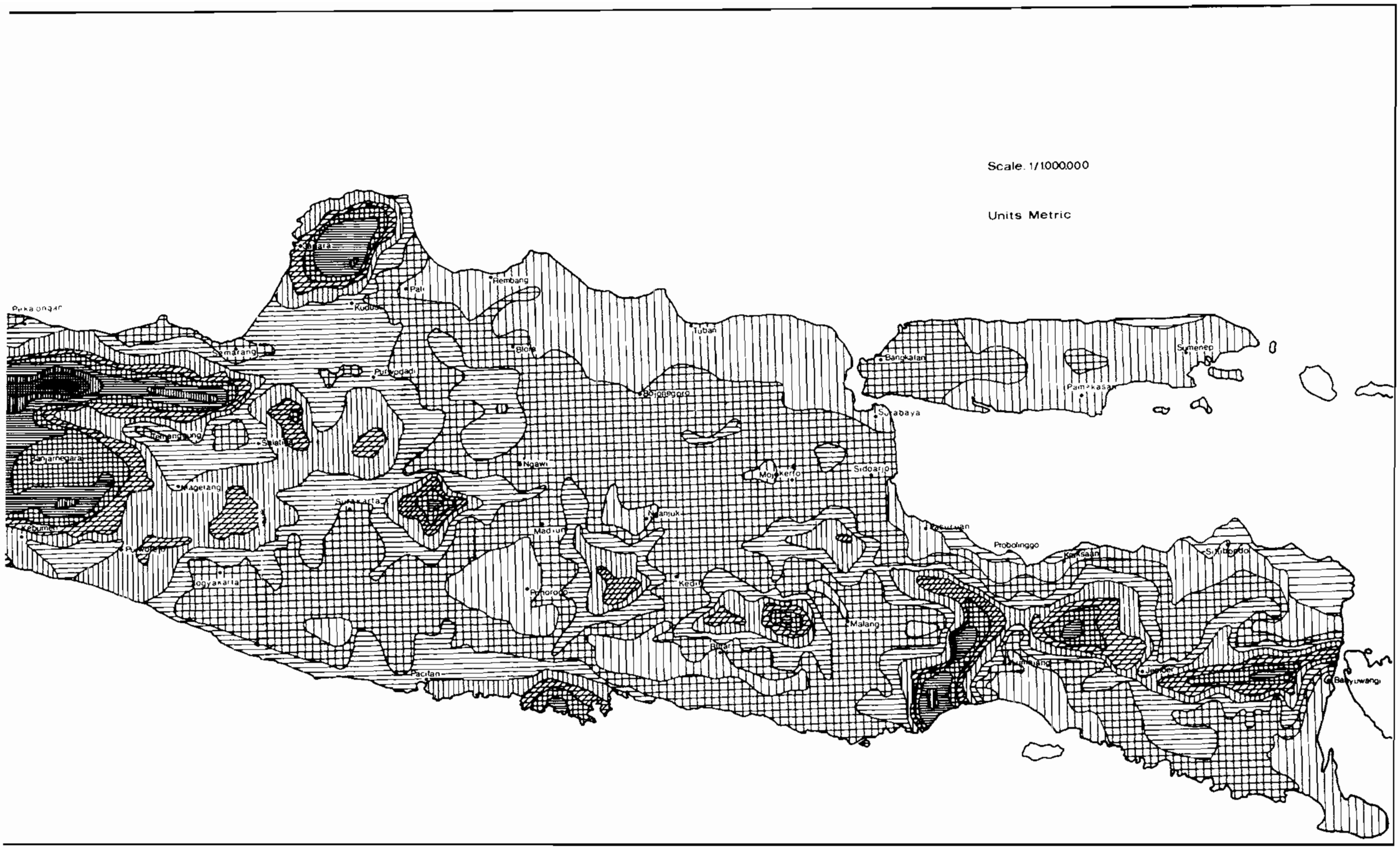
soil loss for the whole catchment. Since the rate of the soil loss is not uniform throughout most watersheds, more information and new techniques are needed to predict erosion on a surface area smaller than the whole catchment. In any case, the technique has been verified on watersheds with an area smaller than 2500 km^2. Arnoldus (1980) obtained poor correlations between the EI_{30} and Fournier's indices. He proposed as a modification of the Fournier approach, the quantity

$$\sum_{1}^{12} pi^2/P$$

in which pi is monthly precipitation and P is annual precipitation. He obtained an improved correlation coefficient of 0.83 between this index and EI_{30} for 14 West African rain-gauge stations, and subsequently used this approximation of the R factor in the USLE to construct an isoerodent map for Africa.

Erosive rainfall in the tropics differs from that in other regions mainly in intensity and frequency characteristics. Rainstorms generally are more intense in the tropics, that is, the energy load of an individual storm is much greater than in temperate zones (Kowal and Kassam 1976). This is due to the larger size and greater number of drops falling per unit of time. Table 30 shows some of the observed maxima on record for erosive rainstorms. Table 31 shows comparative annual erosion index values for the tropics and nontropics. Both tables show the extreme aggressivity of tropical rainfall, which is generally explained by quantity, frequency, and intensity-drop-size characteristics.

Kowal and Kassam (1976) reported that about 60 percent of the drops in a typical storm at Samaru, Nigeria were > 3 mm in diameter. In Zimbabwe Hudson (1963) found that drops increase in size to an intensity of 63 mm/hr (2.5 in/hr) and then decrease. Blanchard (1950, 1953) reported that Hawaiian raindrops rarely exceeded 2 mm diameter (but these were for orographic rains) and also that drop sizes change with intensity in a pattern similar to Hudson's. Lal (1976*c*) indicated that because of high rainfall intensities over short durations as well as increased raindrop impact by wind enhancement, the erosivity index EI_{30} may underestimate the ki-

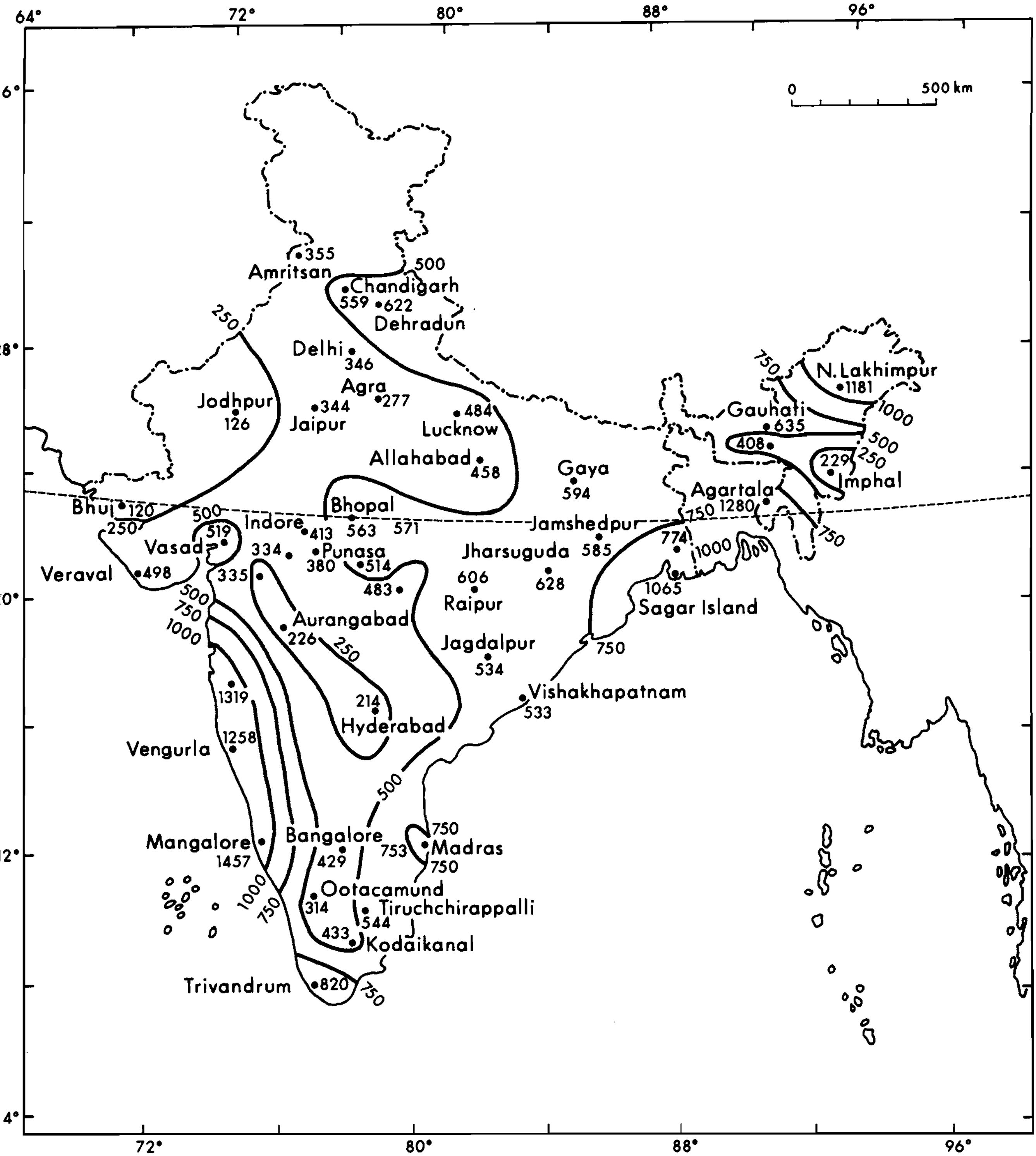


netic energy of tropical storms. However, in view of Hudson's peak drop size findings, older calculations may have overestimated storm energy, a problem which has been corrected by recent calculation methods (Wischmeier and Smith 1978). In many areas of the tropics thunderstorms occur with sharp, high intensity rainfall peaks, such as in western Nigeria (Wilkinson 1975). In the Hawaiian Islands thunderstorms are not as common. As for peak intensities, a short 4-second burst of 261 mm/hr has been recorded on the eastern coast of the island of Hawaii (Fullerton and Wilson 1974) with a specially designed rainfall intensity gauge. In northern Nigeria peak intensities of 120 to 160 mm/hr are not uncommon (Kowal and Kassam 1976); in Malaysia 200 mm/hr rainfalls are not unlikely.[2]

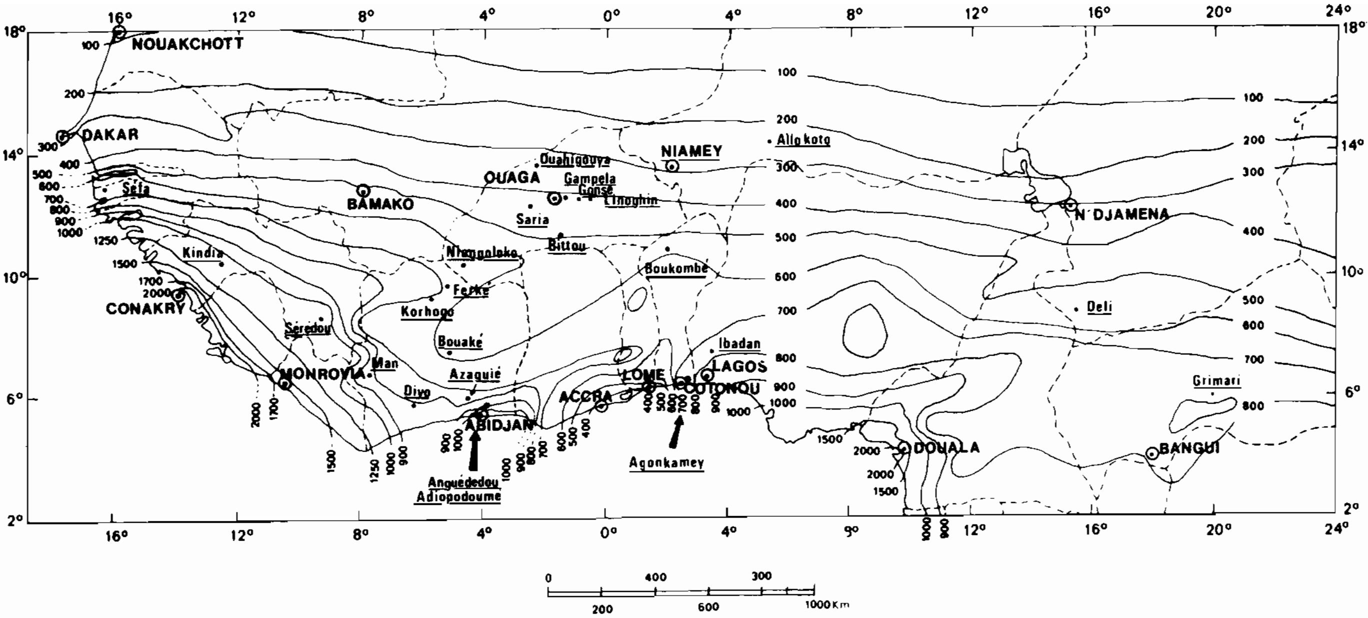
Erosive storms in the tropics may be infrequent in occurrence. Major soil losses in Colombia are due to only a few storms of high intensity (Suarez de Castro 1950). The same situation prevails generally in the Hawaiian Islands where a few so-called *kona* storms are the most hazardous. Similarly, at the experiment station in Mazoe, Zimbabwe (Hudson 1971) it has been found in almost all seasons that over half the total amount of erosion occurred in the one or two heaviest storms of the year. In one instance three quarters of the yearly loss took place in 10 minutes. Farther north in Upper Volta it was found that 88 percent of the annual erosion occurred in approximately 14 hours and 6 hours in 1956 and 1957 respectively (Fournier cited by Jackson 1978). However, Roose (1977*c*) states that in the dry or humid tropics the level of erosion is not determined by exceptional rain but by the sum of ten to twenty of the most erosive rainstorms annually.

More recently in the United States, an effort has been underway to separate the erosivity term into rainfall and runoff erosivity components. The extension of this idea to African conditions has not been attempted. Extreme climatic variability and the wide range of rainfall intensities and durations in the tropics seem to lend themselves well to such a versatile erosivity assessment technique. However, such distinctions are less necessary in the tropics than in temperate climates where water erosion

2. William Broughton, then of the University of Malaysia, Kuala Lumpur. Personal communication, 6 June 1978.



Map 26. Isoerodent map of India. (CSWCRTI 1977)

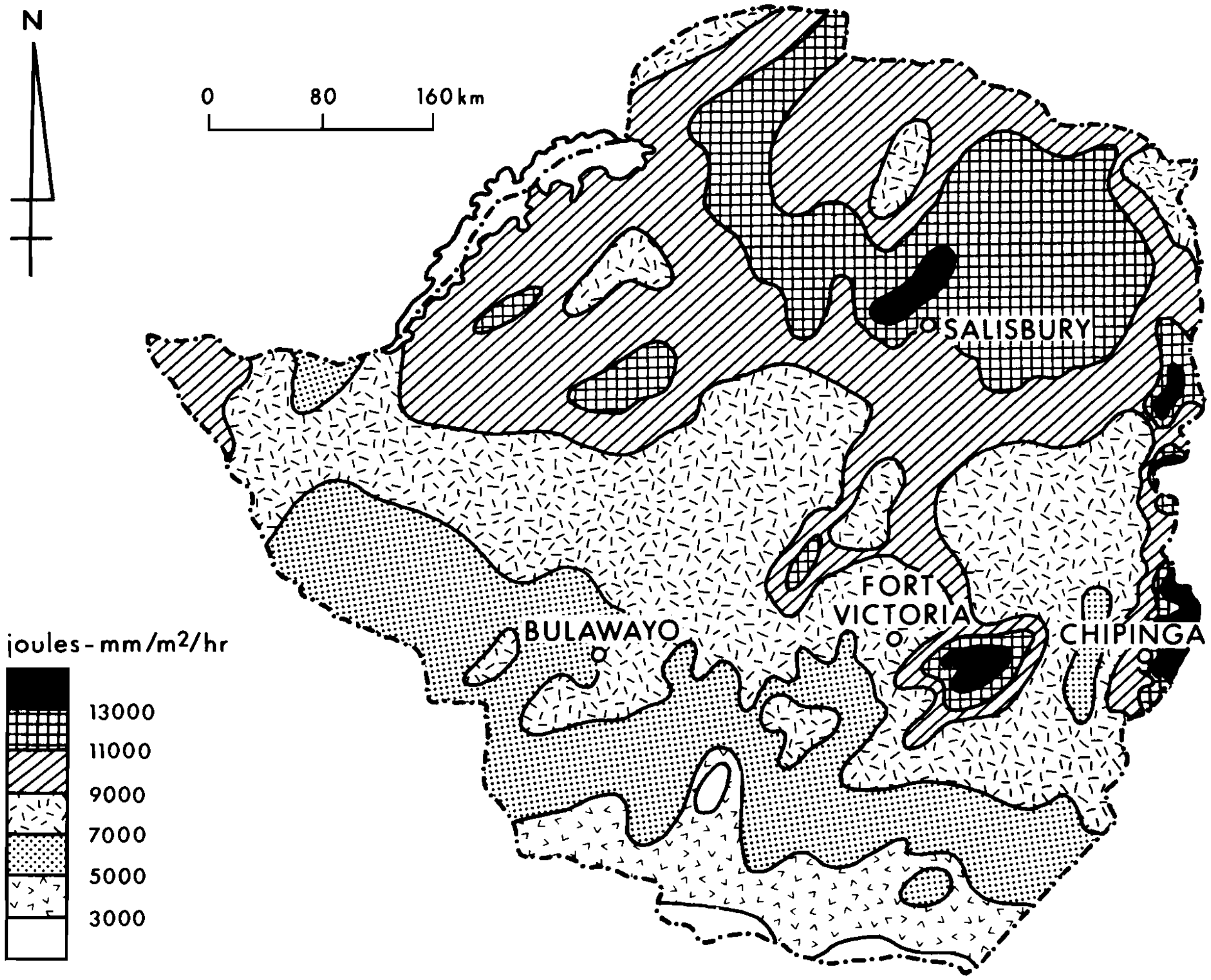


Map 27. Isoerodent map of west and central Africa. (Roose 1977*c*)

Table 29. Summary of alternative estimates for the rainfall erosion index and its components

Location	Climate (Average annual precipitation)	Relationship	Author's units: Qty	Author's units: Units	Reference
Sefa, Senegal	Tropical (1300mm)	$EI_{30} = 1.2A - 4$ $E = 2.5A - 1$	A E EI_{30}	mm $Kg\ m/m^2$ ton/ha	Charreau (1969)
Allokoto, Niger	Dry Tropics (495 mm)	$EI_{30} = 0.0158A\ I_{30} - 1.2$	A I_{30} EI_{30}	mm mm/hr ton/Km^2	Delwaulle (1973)
Western Nigeria	Tropical (1500 mm)	$E = (198+84 \log_{10} I_{30})A+24$	A I_{30} E	cm cm/hr ton m/ha	Wilkinson (1975)
Northern Nigeria	Tropical (1100 mm)	$E = (41.1A - 120.0)x\ 10^3$	A E	mm $ergs/cm^2$	Kowal and Kassam (1976)
Large area of West Africa	Dry to Humid Tropical (500-2100 mm)	$\frac{Ram}{Ham} = 0.50$	Ram Ham	$(ft\ ton/Ac)x10^2$ mm	Roose (1977<u>b</u>)
Madagascar	Humid Tropics (1300 mm)	$E = 2.325A - 3.945$	A E	mm $ton\ m/Km^2$	Bailly et al. (1976)

Explanation of symbols: A is rainfall amount; Ham is average annual rainfall amount; E is kinetic energy of rainfall per unit area of ground surface; EI_{30} is rainfall erosivity index after Wischmeier and Smith (1958); I_{30} is maximum intensity of rainfall sustained for 30 minutes; Ram is total yearly average EI_{30}.



Map 28. Mean annual erosivity over Zimbabwe (Rhodesia). (Elwell and Stocking 1976)

from runoff alone can be the major cause of soil loss—during the portion of the year when snowmelt prevails.

Soil Erodibility and Rillability Characteristics

The inherent susceptibility of a soil to erosion by water is collectively determined by its structural and hydrological properties. Thus aggregate breakdown and subsequent particle detachment from bare soil by a given rainfall (or overland flow) depends on aggregate stability and particle (or aggregate) size distribution characteristics. The likelihood of particle-transporting runoff occurring depends not only on rainfall characteristics but also on water transmission and rillability properties of the soil, particularly infiltration rates at the prevailing antecedent water contents. In the USLE (Wischmeier and Smith 1978) this susceptibility is quantitatively defined by the erodibility (K) factor, which has a potential maximum numerical value determined by the R value and the units of tons/acre/EI_{30} unit (Tm/ha/metric EI unit). As intended by the USLE, its experimental determination must be based on unit values for other factors in the equation. These are specified as follows: for R 100 EI_{30} units in ft-tons/acre/inch or 57.64 m-Tm/ha/cm; for L 72.6 ft or 22.1 m; for S a uniform slope of 9 percent; for C a bare, fallow, weed-free, frequently tilled condition for the two years preceding the initiation of measurement; and for P conventional row-crop tillage up and down the slope. Experimental determinations under natural rainfall must also represent a long term (preferably 20 yr, minimum 5 yr) mean value which encompasses a representative range of storm sizes, antecedent soil water contents, and other random natural variations.

Because of these rigorous requirements, with resulting time-consuming and expensive measurements, experimental values for the "real" erodibility of soils in general and tropical soils in particular

Table 30. Selected data for high rainfall intensity rates in the tropics

Location	I(mm/hr)	Duration	Date
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 hr	2/28-29/64
Belvouve, La Reunion	112	12 hr	2/28-29/64
Belvouve, La Reunion	91	18.5 hr	2/28-29/64
Cilaos, La Reunion	78	24 hr*	3/15-16/52
Cilaos, La Reunion	52	2 days	3/15-17/52
Baguio, Philippines	49	24 hr	7/14/11

Source: Modified from Jackson 1978, Lal 1977d, and unpublished sources.
*This storm produced the highest 24-hr rainfall on record (1869.9 mm or 73.6 in).

Table 31. Selected data for rainfall erosivity according to the EI_{30} index

Location	Index	Source
S. Louisiana	600	Wischmeier & Smith 1978
Mangalore, W. India	1457	CSWCRTI 1977
Conakry, Guinea	2000	Roose 1977c
Douala, Cameroon	2000	Roose 1977c
Laupahoehoe, HI	740	El-Swaify & Cooley 1980
Hilo, HI	780	El-Swaify (Unpublished)
Campinas, Sao Paulo	690	Lombardi Neto 1977
Jakarta, Indonesia	2307	Bols 1978

are rare. Therefore, rainfall simulators have been used by various workers to develop such values more quickly (Meyer and McCune 1958). However, because of the short-term nature of such measurements, certain precautions must be taken during both the data collection and analysis phases to ensure that simulated erodibility values correspond as closely as possible to "real" values (Dangler and El-Swaify 1976). The data reported below (Tables 32 to 37) include values obtained by both methods. For comparative purposes, and because certain soils are common between temperate and tropical regions, values for selected soils on the mainland United States are included.

From the tables it is clear that erodibility values for tropical soils vary so widely that to describe them categorically as resistant to erosion is misleading. Furthermore, it is evident from the wide spread of values within each order that soil orders, as a classification level, may be useful for descriptive relative assessments of erodibility class (e.g. Alfisols > Oxisols) but are insufficient as a quantitative tool for estimating K value. Of particular interest is the fact that soils in the same order but studied at different locations display wide discrepancies. For example in both Hawaii and Puerto Rico (Dangler and El-Swaify 1976; Barnett et al. 1971) it was found that Ultisols were very erosion resistant as indicated by their low K values. In contrast, in Central America and Venezuela (Popenoe 1976; Pla 1977) Ultisols covered a wide range from "extremely low" to "extremely high erodibility." In the mainland United States (Wischmeier and Smith 1978) this order also covered a wide range of resistance to erosion. More agreement is found universally for strongly aggregated Oxisols, the heavy clay Vertisols, and the weakly aggregated Alfisols; these orders possess low, moderate, and high erodibilities, respectively. It is important to note here that one possible source of the observed discrepancies is the use by different workers of many different soil classification systems. Therefore, a means of universal identification of soils is needed to insure uniform understanding of soil erodibility trends. The family level of classification in the U.S. Soil Taxonomy (SCS 1975*b*) is a likely tool for this purpose.

Table 32. Erodibility of soils classified as Alfisols or Aridisols

Series or Identification*	Type	Location	K Value	Source
Dunkirk	silty loam	Geneva, NY	0.69	Wischmeier & Smith 1978
Dayton		Oregon	0.54	Roth et al. 1974
St. Clair	subsoil	Michigan	0.48	Roth et al. 1974
Keene	silty loam	Zanesville, OH	0.48	Wischmeier & Smith 1978
McGary	subsoil	Indiana	0.36	Roth et al. 1974
Kawaihae	rocky silty loam	Hawaii	0.35	Dangler & El-Swaify 1976
Rabat		Morocco	0.35	Heusch 1970
Hagerstown	silty clay loam	Pennsylvania	0.31	Wischmeier & Smith 1978
Putat		Indonesia	0.26	Bols 1978
Gampala	Ferruginous	Upper Volta	0.25	Roose 1977b
Saria	Ferruginous	Upper Volta	0.25	Roose 1977b
Seta	Ferruginous	Senegal	0.25	Roose 1977b
Punang		Indonesia	0.14	Bols 1978

*Identification provided when series was not named.

Table 33. Erodibility of soils classified as Oxisols

Series or Identification*	Type	Location	K Value	Source
Molokai	silty clay loam	Hawaii	0.22	Dangler & El-Swaify 1976
Wahiawa	silty clay	Hawaii	0.14	Dangler & El-Swaify 1976
Bouoke	Ferralitic	Ivory Coast	0.12	Roose 1977b
Apiopodoume	Ferralitic	Ivory Coast	0.10	Roose 1977b
Agonkaney	Ferralitic	Benin	0.10	Roose 1977b
Korhogo	Ferralitic	Ivory Coast	0.02	Roose 1977b
Catalina-Cialitos	clay	Puerto Rico	0.01	Barnett et al. 1971

*Identification provided when series was not named.

Table 34. Erodibility of soils classified as Inceptisols

Series or Identification*	Type	Location	K Value	Source
Pakini	silty loam	Hawaii	0.55	Dangler & El-Swaify 1976
Naalehu	silty clay loam	Hawaii	0.21	Dangler & El-Swaify 1976
Waipahu	silty clay	Hawaii	0.19	Dangler & El-Swaify 1976
Kukaiau	silty clay loam	Hawaii	0.17	Dangler & El-Swaify 1976
Pandura	loam	Puerto Rico	0.11	Barnett et al. 1971
Hilo	silty clay loam	Hawaii	0.07	Dangler & El-Swaify 1976
Darmaga		Indonesia	0.04	Bols 1978
Juncos	clay	Puerto Rico	0.02	Barnett et al. 1971

*Identification provided when series was not named.

Table 35. Erodibility of soils classified as Mollisols or Vertisols

Series or Identification*	Type	Location	K Value	Source
Mayberry	subsoil	Nebraska	0.67	Roth et al. 1974
Pawnee	subsoil	Nebraska	0.45	Roth et al. 1974
Shelby	loam	Missouri	0.41	Wischmeier & Smith 1978
Marshall	silty loam	Iowa	0.33	Wischmeier & Smith 1978
Lualualei	clay	Hawaii	0.30	Dangler & El-Swaify 1976
Austin	clay	Texas	0.29	Wischmeier & Smith 1978
Jegu		Java	0.20	Bols 1978
Portageville		Missouri	0.05	Roth et al. 1974

*Identification provided when series was not named.

Table 36. Erodibility of soils classified as Ultisols

Series or Identification*	Type	Location	K Value	Source
Cecil	sandy clay loam	Georgia, USA	0.36	Wischmeier & Smith 1978
Tea	unnamed	Sri Lanka	0.31	Lal 1977d
Cecil	sandy loam	Georgia, USA	0.23	Wischmeier & Smith 1978
Waikane	sandy clay	Hawaii	0.09	Dangler & El-Swaify 1976
Freehold	loamy sandy	New Jersey	0.08	Wischmeier & Smith 1978
Humatas	clay	Puerto Rico	0.00	Barnett et al. 1971

*Identification provided when series was not named.

Table 37. Erodibility of soils with miscellaneous classifications

Series or Identification*	Classification	Location	K Value	Source
Marl	Clay mix	Morocco	0.6	Heusch 1970
Marl	Loose	Morocco	0.5	Heusch 1970
Marl	Cemented	Morocco	0.4	Heusch 1970
Marl	Sandy	Morocco	0.3	Heusch 1970
Schist	Acid	Morocco	0.2	Heusch 1970
Sentolo	Lithosol	Indonesia	0.14	Bols 1978
Citaman	Latosol	Indonesia	0.10	Bols 1978
Sands	Pebbly	Morocco	0.10	Heusch 1970
Limestone	Sandstone mix	Morocco	0.05	Heusch 1970
Darmaga	Latosol	Indonesia	0.03	Bols 1978

*Identification provided when series was not named.

The erodibility tables also show that surface and subsurface soil horizons possess different susceptibility to erosion. This is due to differences in the textural, mineralogical, and structural makeup of the various soil layers (Roth et al. 1974). Thus, different K values are needed for estimating soil losses from the same soil, depending on intended use. K values of surface soils are required for croplands while values for subsurface soils are needed for estimating soil loss hazards associated with construction activities.

A major criticism of available experimental K values for tropical soils stems from their being calculated according to the definition given earlier. Errors in calculation are likely if the base data for EI, L, and S factors are not applicable to the site under investigation. Indeed, it has been suggested by some authors that the low K values attributed to highly weathered tropical soils may not be strictly true, but rather a result of overestimated rainfall erosion indices as calculated by Wischmeier and Smith's EI_{30} value (1978). This criticism does not apply to data collected uniformly under controlled simulated rainfall such as those published by the present authors (Dangler and El-Swaify 1976) and also given in Tables 31–36.

The dependence of soil susceptibility to water erosion on textural, structural, and hydrological properties has been established by several investigators outside the tropics (Wischmeier and Mannering 1969; Wischmeier et al. 1971; Roth et al. 1974). These efforts culminated in the development of predictive approximations (e.g. for sand K = 0.05; for very fine sand K = 0.44; ARS 1975*a*), equations, and nomographs which were recommended by the respective authors for estimating K values whenever experimental values are not available (Figs. 21 and 22). These nomographs were put to wide use in the United States and in many other, including tropical, countries. Wilkinson (1975) and Roose (1977*c*) reported that soil erodibilities estimated from soil properties as described by Wischmeier et al. (1971) were satisfactory for some ferrallitic and ferruginous soils. Tables 38 and 39 show other examples of such use in South America and South Asia. Regardless of whether or not the absolute values are correct, relative trends again confirm the extreme variability in erosion susceptibilities (0.06–0.48) among tropical soils. El-Swaify (1977) and El-Swaify and Dangler (1977) criticized the use of mainland U.S.-based nomographs to predict the erodibility of tropical soils and provided preliminary data supporting the need for different predictive parameters to estimate tropical soil erodibility. These criticisms are founded first on the limited data base from which those nomographs were developed, thus either necessitating excessive extrapolation of nomograph values or rendering them completely inapplicable for use in tropical soils. Second, soil analysis procedures recommended for developing parameter values for use in the nomographs may not be appropriate to highly weathered soils.

The first criticism is clearly supported by the data in Table 40, which shows that prevailing textural classes, content of organic matter, and/or sesquiox-

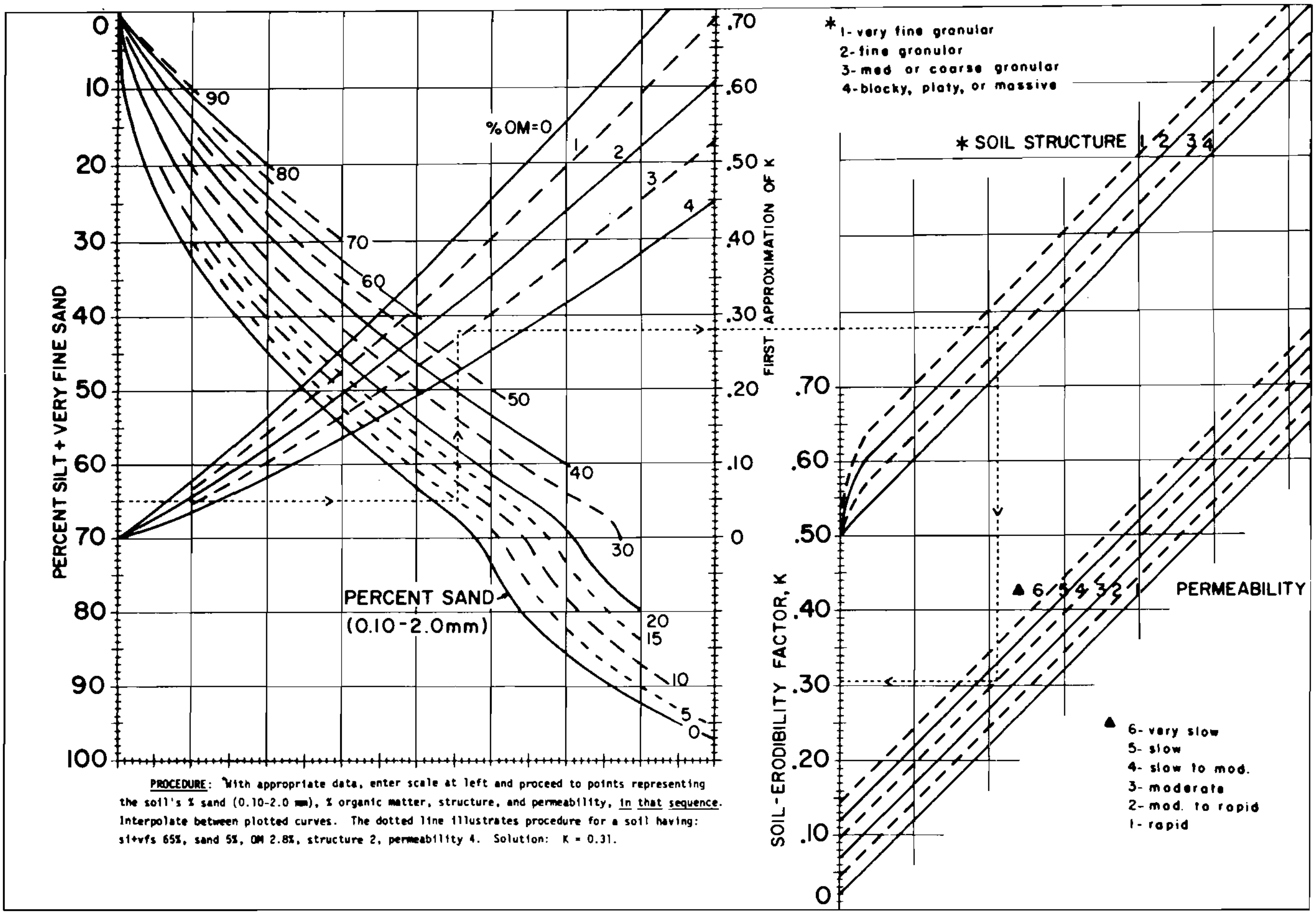


Figure 21. Wischmeier's nomograph for soil erodibility estimation. (Wischmeier et al. 1971)

ides of iron and aluminum generally fall outside the ranges covered by either nomograph. The second criticism is justified, particularly for oxidic soils, by the findings listed in Table 41. This table shows that the predicted erodibility value is clearly dependent on the methodology used to determine the particle size distribution in soil. It is well known that determination of tropical soil properties, particularly particle size and aggregate stability characteristics, is method-sensitive (El-Swaify and Lim 1977). Preliminary indications are that prediction of the erodibility of tropical soils requires parameters different from those that have been used successfully to predict the erodibility of temperate soils (El-Swaify and Dangler 1977; Table 42).

Although erodibility is presumed to be a constant, inherent characteristic of the soil (Wischmeier et al. 1971), this clearly is not the case. While certain soil characteristics that determine erodibility remain relatively unchanged (e.g. particle size distribution and mineralogical composition), others can undergo drastic change either naturally or because of management. These include organic matter content, tilth and aggregation properties, and the distribution of soluble and exchangeable ions (Singer et al. 1981). A major benefit of well-conceived predictive equations, therefore, is to make possible the periodic adjustment of a K value whenever appreciable changes in soil properties take place. Just as for initial determination of erodibility, repeated experimental determinations to detect these changes would be time consuming and probably prohibitive in cost.

Aside from the investigations summarized above, soil susceptibility to erosion has been reported by most authors only descriptively, or by numerical ranks at best. These are based partly on the quantitative findings discussed above and partly on general observations by soil scientists and conservationists, including the observation that poorly aggregated very fine sands and silts as well as easily dispersible silts and clays are highly erodible. In contrast, well-aggregated soils in which surface soil aggregates do not segregate from the underlying soil

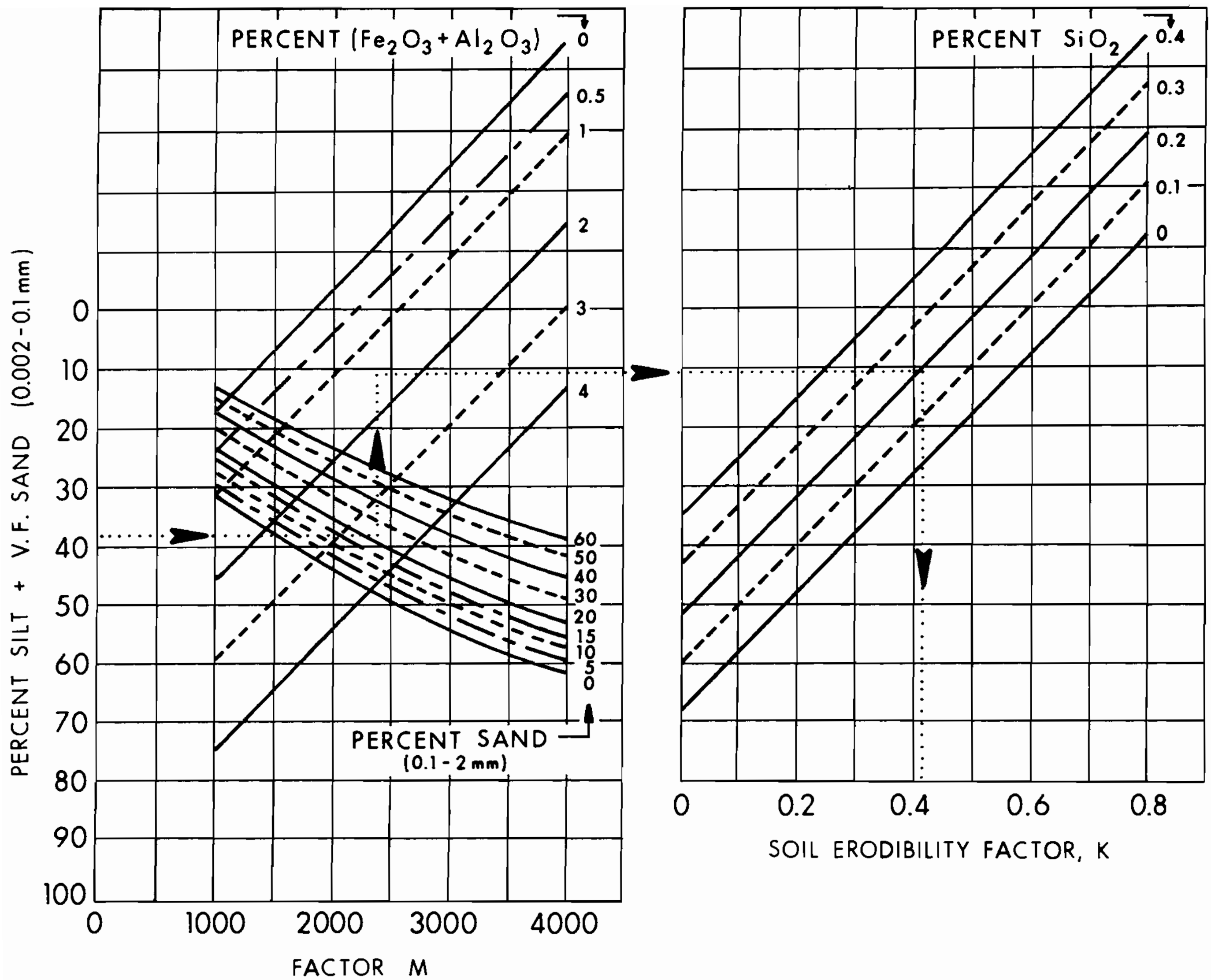


Figure 22. Roth, Nelson, and Romkens' (1974) nomograph for soil erodibility estimation.

mass (as do the irreversibly dried aggregates in Hawaii's Typic Hydrandepts) are less subject to detachment and rillability. Based on many observations, Middleton's (1930) dispersion ratio (the ratio between water-dispersed < 50μm particles and the total silt plus clay content of a soil sample) received wide use for ranking soil susceptibility to erosion. Bonnet and Lugo-Lopez (1950) evaluated "erosiveness" of Puerto Rican soils on the basis of Middleton's criteria. Later Lugo-Lopez (1969) attempted to simplify the laboratory measurement of erodibility by using the percentage of silt and clay in aggregates. Yamamoto and Anderson (1973) found that suspension percentage (the numerator in Middleton's dispersion ratio) was by itself the poorest of 13 erodibility indices in explaining splash losses from selected forest soils. In contrast, structural characteristics, as reflected by soil contents of aggregates in different size classes or by combinations between these and other characteristics, were well related to splash losses.

Rose (1960, 1961), studying splash erosion of some East African soils, discovered an indication that aggregate breakdown under artificial rainfall was a factor contributing to soil loss due to splash. He suggested that his detachment technique might, after further refinement, provide a sensitive and simple means of assessing natural differences in soil structure that influence detachment and erodibility. Pereira (1956), also working with East African soils, looked for a simple test that would define the structural condition of a soil. He sought to combine in

Table 38. Nomograph-predicted erodibility values for some Brazil soils

Soil Identification	Range of K values, by horizon A	B	C
*Podzolico Vermelho (Amarelo var. Lavas)	0.49-0.57	0.42-0.57	0.54-0.62
Serie Artemis	0.30-0.43	0.20-0.28	0.32
*Podzolico Vermelho (Amarelo--Orto)	0.16-0.38	0.16-0.40	0.43-0.59
Serie Godinhos	0.30-0.37	0.14-0.22	0.29
*Podzolico Vermelho (Amarelo var. Piracicaba)	0.28-0.36	0.11-0.17	0.15-0.22
Serie Quebra Dente	0.22-0.26	0.25-0.27	0.30
Serie Pau D'Alho	0.25	0.15	0.57
Serie Bairrinho	0.18-0.24	0.20-0.23	0.27
Serie Lageadinho	0.24	--	0.49
Serie Pompeia	0.20-0.22	0.18-0.28	0.42
Serie Tres Municipios	0.17	0.17	0.18
Serie Guamium	0.06-0.16	0.07-0.14	0.17-0.21
Serie Luiz De Quieroz	0.11-0.13	0.11-0.16	0.25
Serie Paredao Vermelho	0.10-0.12	0.11-0.12	0.10
Serie Monte Olimpo	0.09	--	0.15
Serie Tanquinho	0.06-0.07	0.06-0.09	--
Serie Iracema	0.06	0.07-0.09	--

Sources: *Freire and Pessotti 1974; others from Freire and Pessotti 1976.

Table 39. Nomograph-predicted erodibility values for some Sri Lanka soils

Soil Identification	Classification	K value
Katunayake	Sandy regosol	0.48
Batticaloa	Noncalcic brown	0.35
Kankesanturai	Red-yellow latosol	0.33
Mannar	Red-yellow latosol	0.33
Anuradhapura	Reddish-brown earth	0.27
Hambantota	Reddish-brown earth	0.27
Badulla	Red-yellow podzolic	0.22
Ratnapura	Red-yellow podzolic	0.22
Katugastota	Reddish-brown latosolic	0.17

Source: Joshua 1977.

Table 40. Comparison of range of properties used to develop existing nomographs with those encountered in selected Hawaii soils

Soil property and units	Range encountered: to develop Nomograph 1	to develop Nomograph 2	Selected Hawaii soils
Silt + very fine sand (0.002-0.1 mm) %	13.9-82.3	32.2-59.1	10.0-56.8
Sand (0.1 mm-2 mm) %	1.4-81.7	0.59-40.9	1.56-38.4
Clay (< 2µm) %	4.2-44.5	2.6-66.5	19.6-88.8
Organic matter, %	0.9-5.5	0.59-2.12	1.10-18.8
Soil structure class (1-4)	1-4	4	1-3
Soil permeability class (1-6)	1-6	6	1-5
Extractable Fe + Al (Sesquioxides) %	not given	0.97-3.76	3.62-34.3
Extractable Si, %	not given	0.12-0.32	0.0062×10^{-3} - 0.245×10^{-3}
Sources	Wischmeier et al. 1971	Roth et al. 1974	El-Swaify and Dangler 1977

Table 41. Comparison of nomograph-predicted and experimental erodibility values for Hawaii soils

Soil	Predicted K value based on: Apparent texture	H_2O dispersion	NaOH dispersion	Experimental K
Kawaihae	0.25	0.22	0.24	0.35
Hilo	0.07	0.03	0.03	0.07
Kukaiau	0.15	0.09	0.06	0.17
Naalehu	0.17	0.19	0.11	0.21
Pakini	0.08	0.08	0.05	0.55
Waipahu	0.14	0.10	0.10	0.19
Molokai	0.15	0.09	0.08	0.22
Wahiawa	0.07	0.19	0.05	0.14
Waikane	0.15	0.27	0.05	0.09
Lualualei	0.13	0.13	0.13	0.30

Table 42. Regression equations obtained at the 5th step of stepwise regression analysis for soil properties (excluding mineralogy) and erodibility of Hawaii soils under different antecedent moisture conditions

Equation No.		Equation
1	K_{dry}	$= 0.01250 + 0.01100\ \mathrm{LT250\mu} + 0.00018\ \underline{\mathrm{MH}} - 0.01722\ \underline{\mathrm{SUS}} - 0.31106\ \underline{\Delta\mathrm{pH}} - 0.03681\ \underline{\mathrm{pH}}$
2	K_{wet}	$= 0.18946 + 0.00145\ \underline{\mathrm{BS}} + 0.00036\ \underline{\mathrm{MH}} + 0.00668\ \underline{\mathrm{BD}} - 2.64084\ \underline{\mathrm{MWD}} - 0.05927\ \underline{\mathrm{pH}}$
3	$K_{weighted}$	$= 0.03970 + 0.00311\ \mathrm{LT250\mu} + 0.00043\ \underline{\mathrm{MH}} + 0.00185\ \underline{\mathrm{BS}} - 0.00258\ \underline{\mathrm{SI}} - 0.00823\ \underline{\mathrm{SA{>}100}}$

Source: El-Swaify and Dangler 1977.

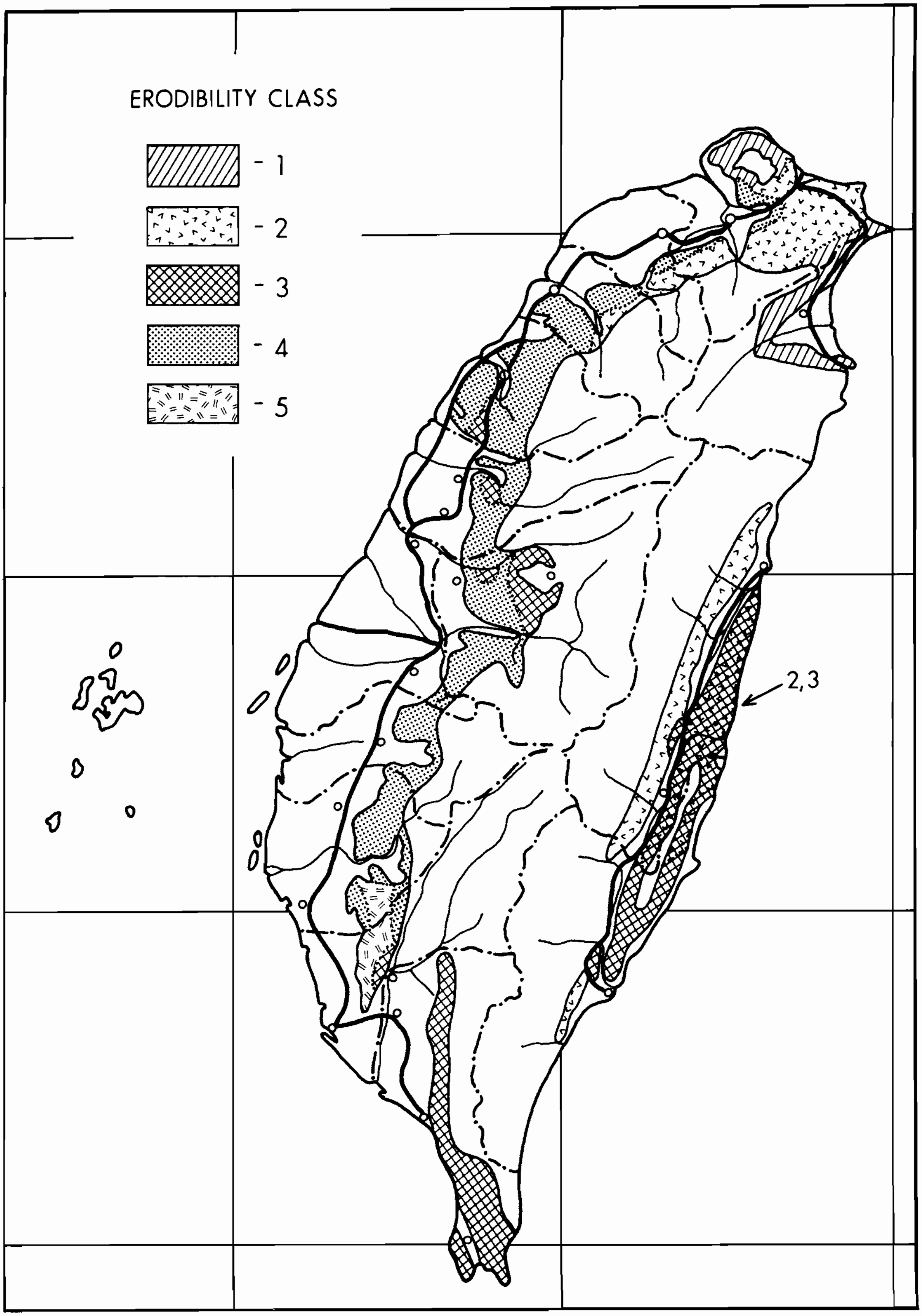
Legend:
- K_{dry} Erodibility under dry antecedent moisture conditions.
- K_{wet} Erodibility under wet antecedent moisture conditions.
- $K_{weighted}$ Mean weighted value for K_{dry} and K_{wet} as explained by Dangler and El-Swaify (1976).
- LT250μ Unstable aggregates (%).
- ΔpH $pH_{KCl} - pH_{H_2O}$.
- BS Base saturation.
- MWD Mean weighted aggregate diameter, mm/25.4.
- SI Silt-sized particles (%).
- MH Sand >100μm(%) [silt-sized particles (%) + very fine sand (%)].
- SA>100 Sand >100μm (%).
- SUS Suspension percentage (%).
- BD Bulk density.

one measurement of infiltration the effects of permeability of the soil and surface sealing resulting from aggregate breakdown under raindrop impact. Pereira was forced to conclude that while his test added to the information on infiltration, no single test was available to assess soil structural condition as it relates to erosion. The potential of this property as an index of erodibility is still unclear. Cormory and Masson (1964) noted that relative erodibilities of some Tunisian soils ranged from 1-12, and arranged their values to straddle K values of 0.1-0.5 in the quantitative system of the USLE. They tentatively assigned K values of 0.05 for Rendzinas with soft crust to 0.61 for calcareous brown soils on eroded marls. Fournier (1967) listed several factors likely to play a role in a comprehensive index of erodibility. These are particle size distribution, chemical composition as it affects flocculation and dispersion, organic and argillaceous colloids that may contribute to cementation of larger particles, cohesion and stability of soil aggregates, and the permeability of the subsoil. Fournier also presented data from Senegal to illustrate deterioration of structure and reduction of permeability with continued intense cultivation. He utilized Henin's "instability index" which is based on dispersed and aggregated particle size distribution and aggregate stability. As yet no relationship between these soil properties and erosion indices has been developed. Soils on sloping lands in Taiwan were classified in five categories of increasing relative erodibility and mapped accordingly by the Joint Commission on Rural Reconstruction (JCRR-MARDB 1977; Map 29). It is not clear how these categories may relate quantitatively to the K factor of the USLE.

An alternative system for estimating soil loss in Zimbabwe has been devised by Elwell (1977), based on a different quantitative definition of soil erodibility. This effort was made to reduce the need for expensive and time-consuming field plot studies for the determination of individual values of different erosion factors. In devising the "simplified" soil loss estimation model for southern Africa (SLEMSA), Elwell (1977, 1981) retained the "unit plot" concept of the USLE but included only three causative parameters of erosion:

$$Z = KCX \tag{4}$$

where: Z = predicted mean annual soil loss, (Tm/ha/yr);
K = mean annual soil loss (Tm/ha/yr) from



Map 29. Relative erodibility of Taiwan slopeland soils. Classes 1–5 are in increasing order of erodibility. (JCRR-MARDB 1977)

Table 43. Soil erodibility values (F) used in the SLEMSA Model

Soil texture	Soil type	Basic index
Light	sands loamy sands sandy loams	4
Medium	sandy clay loam clay loam sandy clay	5
Heavy	clay heavy clay	6

Notes: Subtract the following from the basic index:

1 for light textured soils consisting mainly of sands or silts.
1 for restricted vertical permeability within 1 m of the surface, or for severe soil crusting.
1 for ridging up and down the slope.
1 for deterioration in soil structure due to excessive soil loss in the previous year (>20t/ha) or for poor management.
0.5 for slight to moderate surface crusting or for soil losses of 10-20 t/ha in the previous year.

Add the following:

2 for deep (>2m) well-drained, light-textured sands.
1 for tillage techniques which encourage maximum retention of water on the soil surface e.g. ridging on contour.
1 for tillage techniques which encourage high surface infiltration and maximum water storage in the profile e.g. ripping, wheel track planting.
1 for the first season of no tillage.
2 for subsequent seasons of no tillage.

Source: Elwell 1977.

a standard field plot 30 m x 10 m at a 4.5 percent slope for a soil of known erodibility under bare fallow;

C = the ratio of soil lost from a cropped plot to that lost from bare fallow; and

X = the ratio of soil lost from a plot of length L and slope S, to that lost from the standard plot.

In this case, the K factor incorporates both the kinetic energy of rainfall and soil erodibility and should not be confused with the K factor in the USLE. Rather, erodibility (F) is treated as a subcomponent of K and the authors defined a soil erodibility index by basic soil type. The core values for the index ranged from 4 to 6 but were adjusted depending on permeability, structure, and conservation practices (Table 43). Figure 23 provides an example of these relationships. The X factor in SLEMSA is the same as the LS factor of the USLE (see next section).

Landscape and Topography

It is evident in observing most forms of rainfall erosion, particularly massive gullies, ravines, and landslides, that, other conditions being equal, hilly and mountainous regions are especially subject to soil erosion. On the other hand, completely level areas are less subject to soil erosion than to drainage problems. Generally, however, the major cultivated lands of the world are between these extremes of steep slopes and level land. It has long been observed that higher erosional hazards are always associated with steeper slopes. Erosion workers and conservationists have also determined that, although effects on runoff are inconclusive, soil loss per unit area is higher for longer than for shorter slopes of equal steepness. Slope steepness in percent (s) and length in meters or feet (λ) are quantitatively incorporated in the USLE by the dimensionless factors S and L respectively. Remember that all parameters, when used within the USLE formulation,

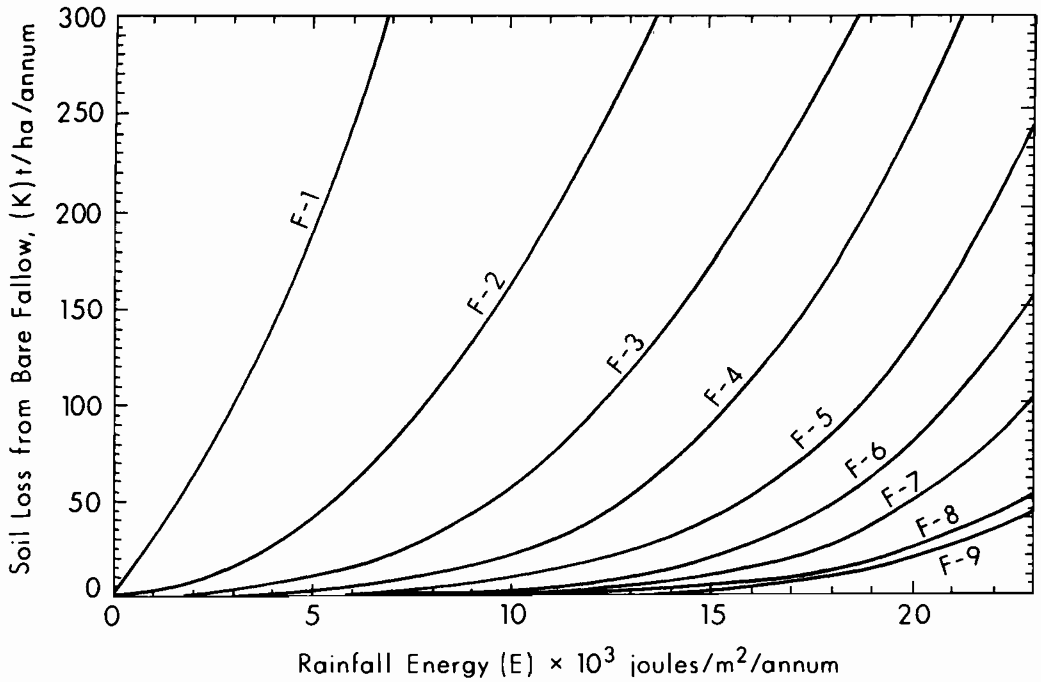


Figure 23. Relationships between K, E, and soil erodibility F. (Elwell 1977)

are intended for predicting losses from rill and interrill erosion only.

The exponential dependence of soil loss on slope steepness (or gradient) is generally accepted and has been verified by most workers (Zingg 1940; Musgrave 1947; Wischmeier and Smith 1965; Hudson 1971). In certain cases the dependence of soil loss on slope gradient was shown to take a pure power form:

$$E = cs^{a} \quad (5)$$

in which E is soil loss, *s* is slope gradient, and *c* as well as the exponent *a* are empirical constants. The value of *a* varied from 0.4 to 2.0 depending on the experimental conditions used by the different workers. In other cases a quadratic form was obtained:

$$E = a + bs + cs^2 \quad (6)$$

in which *a, b,* and *c* are empirical constants. Wischmeier and Smith (1965, 1978) using the latter form, calculated the dimensionless S factor for the USLE as

$$S = \frac{0.43 + 0.30s + 0.043s^2}{6.613} \quad (7)$$

in which the figure 6.613 is the value of the numerator for a standard soil plot ($s = 9\%$).

In the tropics several authors have confirmed the influence of steepness of slope on soil loss (Hudson and Jackson 1959; Fournier 1967; Roose 1975*a*; Lal 1976*d*). Here also, as expected, soil loss generally increased exponentially with slope gradient (Roose 1977*c*). However, among the few exceptions, Lal (1976*b*) and other workers reported that the presence of crop and mulch cover caused inconsistent relationships between soil loss and slope gradient. Roose (1977*c*) demonstrated the sensitivity of soil loss to even very small variations (0.25–0.5%) in slope steepness. Fournier (1967) earlier reported similar data with soil losses at Sefa, Senegal, increasing from 305–698 to 433–1420 Tm/km² when the slope of cropped land increased from 1.0 to 1.5 percent. The dependence of soil loss on slope was greater for sorghum than for groundnuts or rice. Figures 24 and 25 demonstrate the effects of slope on erosional losses from representative residual and volcanic ash soils, respectively, in Hawaii under wet antecedent conditions. It is interesting to note that soil erosion in both groups displays a linear dependence on slope gradient.

Slope length (λ) effects on soil loss are less well defined. However, general agreement exists among workers that, although runoff volume per unit area may be less for long slopes than for short, the greater total volume of runoff running down long slopes induces greater soil losses per unit area from the

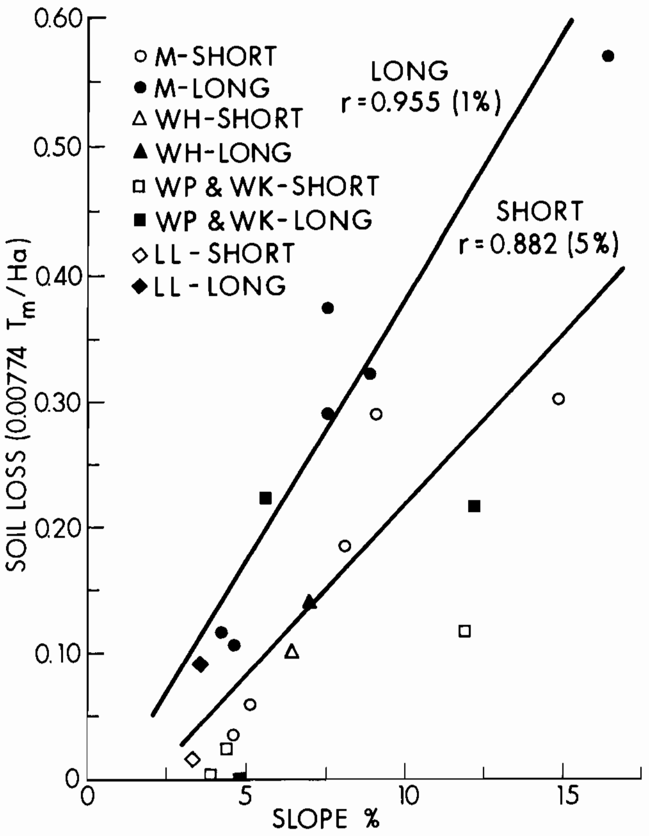


Figure 24. Relation between slope gradient and soil loss under 125 mm of simulated rainfall for residual soils on Oahu, Hawaii. Long and short refer to 24 and 11 m plots, respectively. Storms conducted at wet antecedent condition. (Dangler et al. 1976)

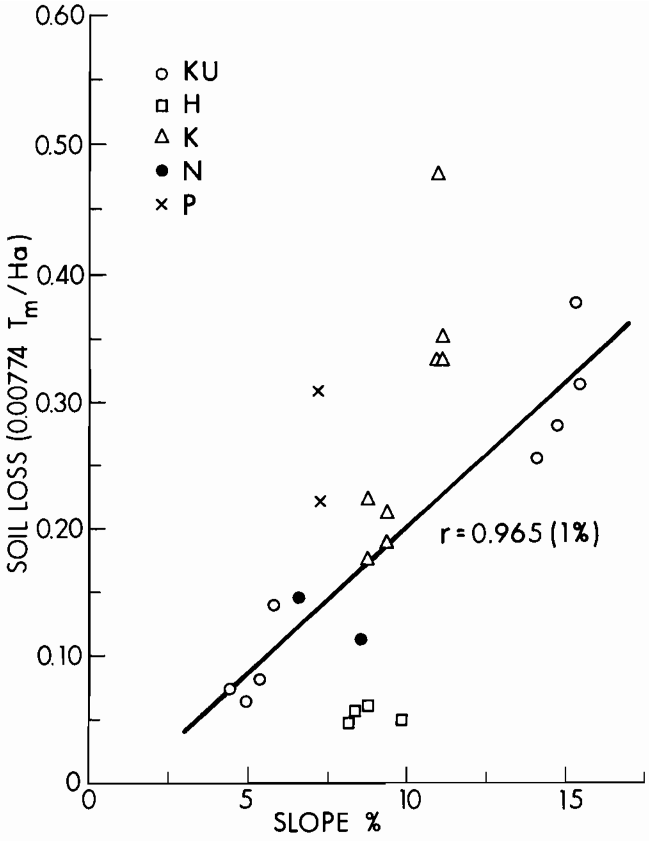


Figure 25. Relation between slope gradient and soil loss from 11 m long plots under 125 mm of simulated rainfall for volcanic ash soils on the island of Hawaii. Storms conducted at wet antecedent conditions. Ku = Kukaiau series; H = Hilo series; K = Kawaihae series; N = Naalehu series; P = Pakini series. (Dangler et al. 1976)

longer than from the shorter slopes. It is further generally agreed that the dependence of soil loss (E) on slope length is in the form

$$E = b\lambda^m \tag{8}$$

in which *b* and *m* are empirical constants. Values for the exponent *m* have been reported by several workers to range from 0.5 to 0.9, depending on the prevailing slope (Smith and Wischmeier 1957). The equation developed by those authors utilizes the exponent of 0.5 for slopes of 5 percent or steeper and has generally been accepted as satisfactory even in the tropics (Hudson 1971; Roose 1977*c*; Elwell 1977). For slopes of 3 percent or less the exponent becomes 0.3, and for 4 percent slopes it is 0.4 (Wischmeier and Smith 1958). Work in the tropics (Hudson 1957; Dangler et al. 1976) indicates that the exponent may have a different value from that used in temperate zones. Based on the data presented in Figure 24, *m* values within the range of data shown for residual Oahu soils, Hawaii, are calculated at 0.67, 0.76, and 1.1 for slopes of 4, 9, and 15 percent, respectively. This would indicate that the contribution of slope length (reflected in the effectiveness of overland flow) to erosional losses from these tropical soils exceeds that which may be estimated from the exponents used on the U.S. mainland (Wischmeier and Smith 1978). Based on his equation, Wischmeier's L, a dimensionless factor for the USLE, has been calculated as

$$L = \left(\frac{\lambda}{22.13}\right)^m \tag{9}$$

where λ = slope length in meters, 22.13 m (72.6 ft) is the length for standard plots for which L = 1, and *m* is the exponent explained above.

In practice the values for the length and slope factors are generally determined as a combined topographic factor, LS from either tables or graphs (Wischmeier and Smith 1965, 1978). Table 44

Table 44. Table for calculation of LS values as recommended by Wischmeier and Smith (1978)

Slope (percent)	Slope length in meters											
	7.62	15.24	22.9	30.5	45.7	61.0	91.4	122	152	183	244	305
0.5	.065	.080	.091	.099	.112	.122	.138	.150	.160	.169	.185	.197
1	.085	.105	.119	.129	.146	.159	.180	.196	.210	.222	.242	.258
2	.133	.163	.185	.201	.227	.248	.280	.305	.326	.344	.376	.402
3	.190	.233	.264	.287	.325	.354	.400	.437	.466	.492	.536	.573
4	.230	.303	.357	.400	.471	.528	.621	.697	.762	.820	.920	1.01
5	.268	.379	.464	.536	.656	.758	.928	1.07	1.20	1.31	1.52	1.69
6	.336	.476	.583	.673	.824	.952	1.17	1.35	1.50	1.65	1.90	2.13
8	.496	.701	.859	.992	1.21	1.40	1.72	1.98	2.22	2.43	2.81	3.14
10	.685	.968	1.19	1.37	1.68	1.94	2.37	2.74	3.06	3.36	3.87	4.33
12	.903	1.28	1.56	1.80	2.21	2.55	3.13	3.61	4.04	4.42	5.11	5.71
14	1.15	1.62	1.99	2.30	2.81	3.25	3.98	4.59	5.13	5.62	6.49	7.26
16	1.42	2.01	2.46	2.84	3.48	4.01	4.92	5.68	6.35	6.95	8.03	8.98
18	1.72	2.43	2.97	3.43	4.21	4.86	5.95	6.87	7.68	8.41	9.71	10.9
20	2.04	2.88	3.53	4.08	5.00	5.77	7.07	8.16	9.12	10.0	11.5	12.9
25	2.95	4.17	5.10	5.89	7.22	8.33	10.2	11.8	13.2	14.4	16.7	18.6
30	3.98	5.62	6.89	7.95	9.74	11.2	13.8	15.9	17.8	19.5	22.5	25.2
40	6.33	8.95	11.0	12.7	15.5	17.9	21.9	25.3	28.3	31.0	-	-
50	8.91	12.6	15.4	17.8	21.8	25.2	30.9	-	-	-	-	-
60	11.6	16.4	20.0	23.1	28.4	-	-	-	-	-	-	-

shows the latest recommendations for calculation of the combined LS factor. It is based on the formula:

$$LS = \left(\frac{\lambda}{22.13}\right)^m \left(\frac{0.43 + 0.30s + 0.043s^2}{6.613}\right) \quad (10)$$

in which all the terms have been explained above. Although Table 44 shows data for slopes ranging from 0.5 to 60 percent and lengths from 7.62 to 305 m, it is important to indicate that data for slopes less than 3 percent, greater than 18 percent, and longer than 122 m represent extrapolations beyond the range of research data that the authors had at their disposal. Therefore, the applicability of the data to the tropics must be particularly questioned where longer or steeper slopes are cultivated, as they often are under high population pressure in developing tropical countries. Even within the range of research data available, verification on tropical soils is lacking. The data in Table 44 are also intended for use on simple uniform slopes. To handle the real situation of irregular slopes, Foster and Wischmeier (1974) devised a refinement of the topographic factor as follows:

$$LS = \frac{\sum_{j=1}^{n} (S_j\lambda_j^{1.5} - S_j\lambda_{j-1}^{1.5})}{\lambda e\ (72.6)^{0.5}} \quad (11)$$

in which

- λ_j = distance from top of slope to lower end of any segment *j* in units of 3.28 meters (10 ft);
- λ_{j-1} = slope length above segment *j* in units of 3.28 meters;
- λ_e = overall length of slope in units of 3.28 meters;
- S_j = value of slope factor, S for segment *j;* and
- S = $(0.043s^2 + 0.30s + 0.43/6.613$ where *s* is the slope steepness in percent.

This equation may apply to irregular slopes by breaking them up into a series of segments each with uniform regular slope but having different gradients and probably different lengths.

An alternative topographic parameter, which was discussed earlier, is the "orographic coefficient" (OC), defined by Fournier (1962) as

$$OC = \frac{H^2}{S} \quad (12)$$

in which H is the average height of surface relief in a catchment, in meters, and S the projected area of the catchment in square kilometers (see chap. 2). He considered the term $\frac{H^2}{S}$ to be an expression of massiveness of the landscape and found that OC was a necessary modifying mathematical parameter in his analysis of correlation between specific degradation (based on river sediment loads for catchments $> 2000\ km^2$) and the climatic coefficient C (discussed earlier). He found a need for distinguishing between regions of "slightly accentuated relief" (OC < 6) and those with "accentuated relief" (OC > 6). Again, no evidence has been found in the literature of the applicability of Fournier's topographic coefficients for predicting site-specific soil losses in the tropics.

As will be discussed in chapter 5, the relationships between soil loss and runoff and topographic parameters provide the quantitative basis for selecting and designing erosion control practices. Unfortunately, most design criteria that have originated in the United States are applied in tropical countries with little testing to seek improved alternatives.

Crop Cover and Residue Management

Long years of experience have shown that other factors being constant, rainfall erosion from vegetated soils is determined by crop types, planting density, canopy characteristics, growth habits and quality of stand, combination with other crops in space (intercropping) or time (rotation), contribution and management of ground-covering residue, and the achieved growth stage development by the time (erosive) rainfall arrives. Hudson (1957) conclusively demonstrated the role of crop or other low growing vegetative canopy as a rainfall interceptor that dissipates the kinetic energy of raindrops, thus depleting the raindrop of its soil-detaching power. The presence of healthy vegetation also causes increased infiltration, reduced runoff, increased soil moisture losses due to transpiration, binding of soil by roots, increased soil organic matter (which can act as both a cover and an aggregate binder), and the slowing or obstruction of overland flow (Fig. 13). Fournier (1967) provided an extensive account of the recognized role of vegetative cover in soil erosion and conservation in Africa and Madagascar. Hudson and Jackson (1959) noted an inverse relationship between productivity of maize and soil loss (Fig. 32). Krantz et al. (1978) demonstrated that fallow watersheds on Vertisols encountered far more

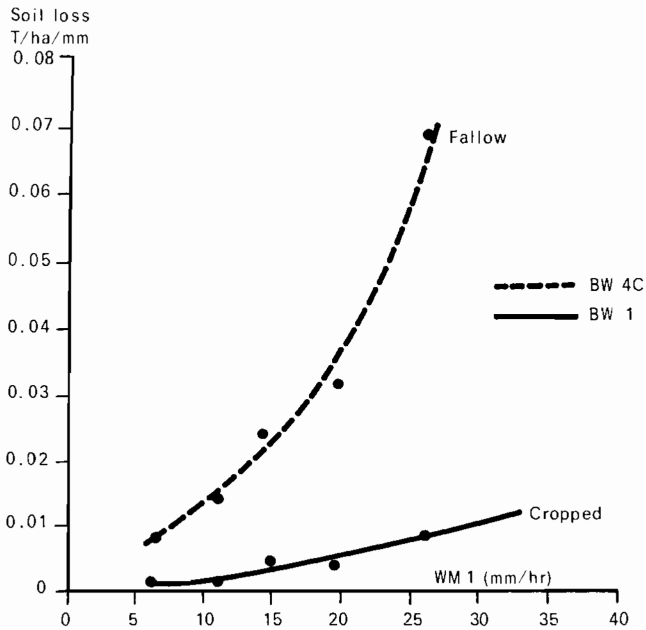


Figure 26. Comparative soil erosion from cropped and fallow Vertisols during the rainy season. (Krantz et al. 1978)

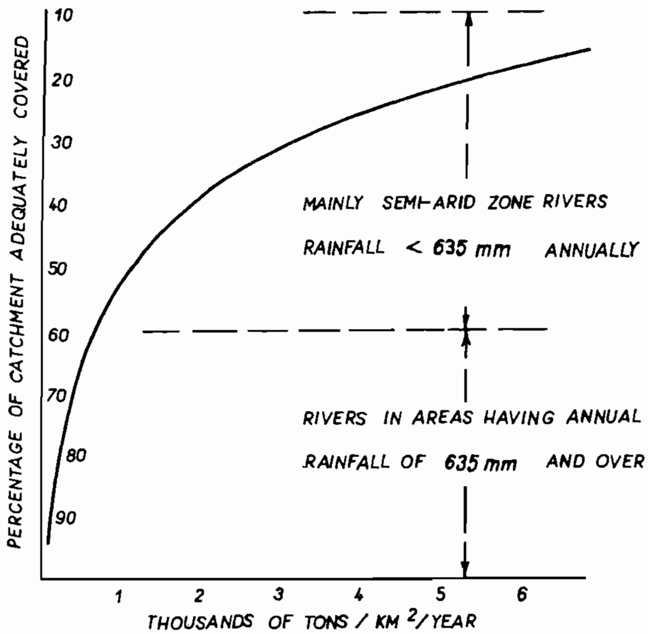


Figure 27. Relationship between catchment vegetation and soil erosion in selected rivers of Africa and Asia. (Balek 1977)

soil losses than cropped watersheds in the semiarid tropics (Fig. 26). Rimwanich[3] reported that soil loss from a fallow soil on a 7 percent slope in northeast Thailand amounted to 48 Tm/ha/yr compared with only 0.075 Tm/ha/yr under grass cover. Additional evidence for the importance of vegetative cover has been provided by Temple (1972) and Balek (1977) (see Tables 45, 46, Fig. 27). Dunne, Dietrich and Brunengo (1978) illustrated the effect of soil exposure by grazing on erosion rates in semiarid Kenya, and concluded that erosion rates accelerated dramatically as ground cover decreased between 20 and 30 percent.

Because of all the factors controlling crop cover effectiveness, a quantitative assessment of crop effects on soil erosion losses—the C factor—can become quite involved. For application in the USLE the C factor is defined as a dimensionless "ratio between soil loss from land cropped under specified conditions and corresponding loss from clean-tilled, continuous fallow" (Wischmeier and Smith 1978). Its magnitude may be derived experimentally from research plots designed to measure soil loss under the conditions required. Otherwise, to calculate its annual numerical value, cropstage periods must be defined and their duration as well as cover effectiveness (expressed as a soil loss ratio) estimated. Also needed are calendar dates coinciding with each of these periods and distribution curves for rainfall erosivity (EI values) during the year. Wischmeier and Smith (1978) provided the data required for such calculations in many states. Unfortunately, hardly any of the required experimental data or computational components listed above have been determined for the tropics. Sample data for Hawaii are shown in Table 47, and estimated loss ratios for selected tropical crops are provided in Table 48. The usefulness of these data will be limited to qualitative evaluation of crop cover effectiveness, as the dates associated with various agronomic practices and rainfall erosivity distributions within the year are required for cultivated locations in order to calculate the mean annual values of C. Such distributions are scarce for tropical regions.

Among other attempts to identify a C factor for cultivated crops in the tropics were those by Lal (1976*d*; Table 49) and Roose (1977*c*; Table 50). Both were developed in West Africa, the first on Alfisols and the second on both Alfisols and Oxisols. Elwell and Stocking (1974) analyzed soil loss data from grazing trials by Barnes and Franklin (1970) and developed a relationship between exposed soil and soil loss. A mean seasonal rating for exposed soil was evaluated by using an idealized exposed soil versus time model. Elwell and Stocking (1976) then considered the time distributions of crop cover and rainfall throughout the season, and developed a per-

3. S. Rimwanich, Land Development Department, Bangkok, Thailand. Personal communication, 1978.

Table 45. Runoff and soil erosion from various crops on identical plots at Mpwapwa, Tanzania

Year	Rainfall (mm)	Cultivated plot a	Cultivated plot b	Cultivated plot + narrow grass belts across slope a	Cultivated plot + narrow grass belts across slope b	Plot cultivated 50% grass a	Plot cultivated 50% grass b	Grass plot a	Grass plot b
1946/47	780	9.0	18.5	--	--	3.9	3.8	1.2	0.6
1947/48	530	16.4	14.3	--	--	10.4	2.1	3.4	0.3
1948/49	650	21.8	44.1	--	--	19.2	1.8	7.3	0.5
1949/50	580	12.8	8.3	--	--	13.1	0.6	4.7	0.2
1950/51	670	26.7	65.3	19.1	7.7	15.4	2.2	5.3	0.9
1951/52	860	28.9	86.4	10.0	30.3	9.0	1.8	6.5	0.7
1952/53	410	13.3	6.2	11.8	3.0	6.9	0.9	3.9	0.3
1953/54	520	25.5	48.8	21.2	37.2	14.3	3.4	7.2	0.4
Average	690	19.3	36.5	15.5	19.6	11.6	2.1	4.9	0.5
Average*		--	36.9	--	20.2	--	2.2	--	0.5

Source: Temple 1972a.
a = runoff as percentage of annual total; b = soil loss in m^3/ha (1.4 Tm/ha).
*Including soil washed to the bottom of the plot but prevented by the tank lip from entering the tank: for grass plot none.

Table 46. Runoff, soil erosion, and sediment concentration relationships at the Mpwapwa erosion plots, Tanzania

Season	Plot 1 Bare: uncult.	Plot 2 Bare: flat cult.	Plot 3 Bare: ridge cult.	Plot 4 Bulrush millet or sorghum	Plot 5 Grass	Plot 6 Bare: flat cult.	Plot 7 Decid. ungr.	Plot 8 Thicket
Percentage runoff of total precipitation*								
1933/34	52.9	34.8	25.2	29.1	2.8	33.3	?	?
1934/35	47.8	28.2	20.8	22.9	0.9	27.1	0.5	0.4
Average	50.4	31.5	23.0	26.0	1.9	30.2	0.5	0.4
Soil erosion in m^3/ha								
1933/34	97.0	80.4	20.9†	66.5	0	37.5	?	?
1934/35	98.7	90.0	44.7	37.5	0	25.0	0	0
Average	97.8	85.2	43.3+	52.0	0	31.3	0	0
Total sediment concentration in runoff in mg/l								
1933/34	42,205	53,180	53,280	37,515	-	25,745	-	-
1934/35	56,275	86,805	73,935	52,285	-	30,235	-	-
Average	49,240	69,993	63,608	44,900	-	27,990	-	-

Source: Temple 1972a.
*Rainfall 1933/34, 675 mm; 1934/35, 564 mm.
†Quantity relates to less than half the 1933/34 rainy season, before which ridges on contour and no soil loss. Average determined by doubling 1933/34 value and probably an underestimation.

Table 47. Sample data for estimated cropping-management (C) factors in sugarcane and pineapple fields on Maui, Hawaii

Crop and planting schedule	Average annual C value	
	Lahaina & Wailuku	Pauwela
Sugarcane, irrigated		
Spring planted	0.13	0.18
Ratoon	0.11	0.14
Summer planted	0.15	0.17
Ratoon	0.11	0.14
Fall planted	0.27	0.27
Ratoon	0.21	0.21
Winter planted	0.29	0.24
Ratoon	0.18	0.18
Pineapple*		
Spring planted	0.17	0.19
Summer planted	0.29	0.18
Fall planted	0.31	0.31
Winter planted	0.20	0.24

Source: Brooks 1977.
*Factors listed include ratoon crop which consumes 12 months of the 30-month crop cycle.

cent cover–soil loss relationship. This approach was proposed as an alternative to the USLE cropping-management factor which requires extensive testing. The same authors attempted to separate crop management treatments that affect physical soil properties from those directly related to crop canopy characteristics. Their classification of different crop canopy types is shown in Table 51.

In addition to plant canopy, plant residues, as protective cover, are also a major component of C-factor calculations (Fig. 28). Alone, residues may also be an effective mulch against erosion (Table 52). In early studies in tropical Africa, Hudson (1957) noted the usefulness of mulch in erosion control, especially in the early part of the season before the crop has become established. Roose (1975*b*) found a few centimeters of straw mulch to be effective and later (1977*c*) classified mulching as an erosion control practice accounted for by a P (rather than C) factor (see Table 53). Lal (1976*b*) found similar results when he evaluated a range of mulch rates on different slopes. His reported relationship between mulch rate and a soil loss mulch factor was the same as that proposed earlier by Wischmeier (1973; Fig. 29). It is relevant to indicate here that residue management as a component of the overall crop-management scheme often represents a realistic means of soil erosion control that is perhaps the most amenable to the needs of the tropical small farmer.

Land Management and Support Practices

Even in ancient times, farmers discovered that shaping their lands in certain ways, such as contour planting and terracing (chap. 5), was necessary for sustained agricultural production. More recently, it has been realized that crop canopy and residue management and subsequent reduction of the C factors, are alone insufficient for controlling runoff and erosion on sloping lands. Thus, many forms of land shaping and preparation prior to planting have emerged in support of cropping factors. These will be discussed in more detail in chapter 5. For the present, it is important to indicate that the quantitative index for judging the effectiveness of such supporting practices is the P factor of the USLE. The conventional basis established by Wischmeier and Smith (1978) is tillage up and down the slope—presumed to induce the most soil loss among alternative practices—and is therefore assigned the maximum numerical P value of 1.0. Values based on U.S. data were assigned to the P factor by Wischmeier and Smith (1978) for contouring, contour strip-cropping, and contour terracing at slope steepnesses ranging up to 25 percent (Tables 54, 55, 56). No similar data are available for tropical regions. Perhaps more important, no such data have been determined anywhere for lands with slopes steeper than 25 percent, although these are often used by subsistence farmers in hilly tropical regions with rapidly increasing population density.

LAND-USE PATTERNS AND FARMING SYSTEMS

The parameters outlined in the previous section contribute physically to soil erosional losses associated with rainfall and runoff. However, manifestation of several of these factors is extremely dependent on the manner in which they are incorporated into existing land use patterns and farming systems. In particular, it is vital that any use of quantitative causative parameters to design control measures (chap. 5) be done with full awareness of these patterns and systems to insure compatibility and some measure of success. The diversity of farming sys-

Table 48. Cropstage periods, durations, and estimated soil-loss ratios for selected tropical crops

Crop	Stage-description	Duration	Soil-loss ratio
Yams	1. Land preparation to planting	2 mo	.70-.60
	2. Planting to close in	4-5 mo	.60-.50
	3. Close in to full cover	2-3 mo	.50-.40
	4. Full cover to harvest	4-5 mo	.40-.20
	5. Harvest to land preparation	2-3 yr	.20-.10
Miscellaneous vegetables	1. Land preparation to planting	1 mo	.70-.60
	2. Planting to full growth	3 mo	.60-.40
	3. Full growth to harvest	1 mo	.40-.10
	4. Harvest to land preparation	1-3 mo	.20-.10
Pigeon peas	1. Land preparation to planting		
	a) Minimum tillage	2 wk	.40-.30
	b) Complete plowing	1 mo	.80-.70
	2. Planting to 2-3 months		
	a) Minimum tillage	1-2 mo	.30-.20
	b) Complete plowing	2-3 mo	.70-.60
	3. 2-3 months to harvest		
	a) Minimum tillage	1-2 mo	.20
	b) Complete plowing	2-3 mo	
	4. Harvest to land preparation	1-6 mo	.20
Coffee			
Sun grown	1. Land preparation to planting	1 mo	.40-.30
	2. Planting to 2 months	2 mo	.30-.10
	3. 2 months to first harvest	21 mo	.10-.05
	4. First to second harvest	12 mo	.05
Shade grown	1. Land preparation (hoeing, shade control)	1-2 mo	.30-.20
	2. Planting to 2 months	2 mo	.20-.10
	3. 2 months to first harvest	21 mo	.10-.05
	4. First to second harvest	12 mo	.05
Pastures			
Nonirrigated	1. Land preparation to planting		
	a) Minimum tillage	1 wk	.40-.30
	b) Plowing and sprigging	2 mo	.70-.60
	c) Furrowing and sprigging	1 wk	.50-.40
	2. Planting to close in		
	a) Minimum tillage	2 mo	.40-.20
	b) Plowing and sprigging	2 mo	.60-.20
	3. Close in to grazing or cutting	2 mo	.20-.05
	4. Grazing or cutting to full cover	1-2 mo	.05-.01
Pastures			
Irrigated	1. Land preparation to planting	2-4 wk	.80-.70
	2. Planting to close in	2-3 mo	.70-.20
	3. Close in to begin first grazing	2-3 mo	.20-.05
	4. Begin to end first grazing	2-4 wk	.05-.01

(Continued)

Table 48. (Continued)

Crop	Stage-description	Duration	Soil-loss ratio
Plantains	1. Brushing, plowing to planting	1 mo	.70-.60
	2. Planting to establishment	5-6 mo	.60-.30
	3. Establishment to first harvest	7-8 mo	.30-.20
	4. First harvest to finish harvest	2 mo	.20-.10
	5. Establishment to second harvest	7 mo	.10-.05
	6. Second harvest to finish harvest	2 mo	.05
	7. Finish harvest to rebrushing and plowing	2-3 yr	.05

Source: G. Martens, East-West Center, Honolulu, Hawaii. Personal communication, 1979.

Table 49. Soil loss coefficients for maize and cowpeas under different treatments on Alfisols

Slope (%)	Bare fallow	Maize-maize (conventional plowing, mulched)	Maize-maize (conventional plowing)	Maize-cowpeas (no tillage)	Cowpeas-maize (conventional plowing)
First season					
1	1.0	0.0	0.20	0.0	0.06
5	1.0	0.0	0.10	0.0	0.06
10	1.0	0.0	0.08	0.0	0.04
15	1.0	0.0	0.14	0.0	0.04
Second season					
1	1.0	0.0	0.11	0.0	0.19
5	1.0	0.0	0.04	0.0	0.08
10	1.0	0.0	0.04	0.0	0.06
15	1.0	0.01	0.16	0.03	0.39

Source: Lal 1976d.

tems and land uses in the tropics is great and would be difficult to discuss fully here. Instead, a brief outline of major patterns that emerge from a survey of the literature is presented.

Agricultural Cropping Systems

Numerous classifications of agricultural systems have been proposed for the tropics, for example, by Tempany and Grist (1958), and Ruthenberg (1971). One of the simplest (Ochse et al. 1961) refers to three general systems of agriculture, other than livestock farming, practiced in the tropics and subtropics: paddy (padi) or lowland rice; shifting cultivation; and intensive cultivation. Paddy culture is practiced in flat areas within the lowland tropics and requires excess water. Fields are farmed year after year under careful management in which fertility is restored by the addition of organic matter and the rain water that flows over the area. Erosion is generally limited in extent although losses of suspended fine clay may occur. Shifting cultivation is practiced on land incapable of being flooded for paddy. Initially, clearings are made in the jungle around a village. The farmer cuts trees into poles during the dry season and places them in piles, along with underbrush. Whereas the larger poles may be sold for fuel, the rest are burned. Crops are planted in small areas for one, two, or three years. The operation is conducted essentially at the family subsistence level. From the erosion standpoint, the most critical stage is during the onset of the rainy season when the soil surface is essentially bare during the first year immediately after planting. Another problem is the common invasion by *Imperata cylindrica,* cogon, and its subsequent takeover after forest clearing. This grass is so dense that it cannot be removed

Table 50. Estimated value of the C factor in West Africa

Practice	Annual average C factor
Bare soil	1
Forest or dense shrub, high mulch crops	0.001
Savannah, prairie in good condition	0.01
Over-grazed savannah or prairie	0.1
Crop cover of slow development or late planting (first year)	0.3-0.8
Crop cover of rapid development or early planting (first year)	0.01-0.1
Crop cover of slow development or late planting (second year)	0.01-0.1
Corn, sorghum, millet (as a function of yield)	0.4-0.9
Rice (intensive fertilization)	0.1-0.2
Cotton, tobacco (second cycle)	0.5-0.7
Peanuts (as a function of yield and date of planting)	0.4-0.8
First year cassava and yam (as a function of date of planting)	0.2-0.8
Palm tree, coffee, cocoa with crop cover	0.1-0.3
Pineapple on contour (as a function of slope)	
(burned residue)	0.2-0.5
(buried residue)	0.1-0.3
(surface residue)	0.01
Pineapple and tied-ridging (slope 7%)	0.1

Source: Roose 1977c.

by hand tools and may spread to form a savannah (Ochse et al. 1961). Intensive agriculture may be practiced on small holdings or on large plantations. Crops raised by monocropping include bananas, citrus, pineapple, coffee, cocoa, tea, rubber, spices, copra, palm oil, sugarcane, fibers, and others (Ochse et al. 1961).

A more extensive classification of agricultural systems in the tropics (Whittlesey 1936, cited by Tempany and Grist 1958) includes livestock. This seven-category system is presented briefly as follows:

a. Nomadic herding is found largely in arid regions.
b. Livestock ranching involves maintenance of pastures and improvement of the breeding stock.
c. Shifting cultivation is found most generally on the poorer upland soils of the tropics.
d. Rudimentary sedentary tillage is found on the more fertile soils of the uplands.
e. Intensive subsistence tillage exists predominantly in rice culture.
f. Intensive subsistence tillage without rice occurs on fertile soils with less rainfall than rice demands.
g. Commercial plantation crop tillage is generally restricted to monoculture of rubber, sugar, tea, coffee, bananas, and so on.

In the south of Brazil where few people live and land is abundant, land is farmed for one or two years and then left idle. Maize is planted up and down steep slopes, yet in the first year erosion is not reported to be a serious problem despite the heavy rain period. This may be due to the vigorous crop growth in the presence of initially adequate fertility and good soil structure. However, during the second year the fertility declines and soil structure changes so that runoff and erosion become significant. This phenomenon is also true of the tea estates in Brazil, which are planted on even gentler slopes than maize (Thomas 1967). This situation suggests that the initially good structure of the soils is so fragile that soil aggregates break down easily even after short periods of cultivation. Mixed farming involving both cattle and crops is apparently successful in a few tropical areas. The Teso district of Uganda and northern Nigeria are examples of such successes (Thomas 1967). However grazing alone or in mixed farming is associated with many serious erosion problems, particularly in semiarid regions.

The foremost erosion problem in Gwalior (Madhya Pradesh), India is from livestock. Since cows are sacred, they are not killed and during the dry season the problems of feeding become so severe that weeds and grass sod are cut from roadsides and wasteland to feed the animals (Pendleton 1940).

Table 51. Classification of crops based on similarities in soil protective characteristics

Description	Examples
A. Row crops	
1. tall, upright crops generally grown on unridged lands	annuals: maize, sorghum, sunflowers; perennials: napier fodder, sugarcane
2. leguminous, annuals; short, bunch, and procumbent varieties	beans: soya, velvet, jack, dolichos, and French; groundnuts; cowpeas
3. tall, upright crops grown on ridged lands	tobacco varieties, group 1 crops on ridges
4. woody, bushy row crops with individual growth and leaf development	cotton varieties
B. Broadcast crops	
1. tall, upright crops broadcast for fodder	see A1
2. short, leguminous crops broadcast for for fodder and green manure	see A2
3. medium height plants for fodder, green manure and weed fallow	sunn hemp, weed fallow
C. Orchards/plantations	
1. individual trees and bushes planted on a regular pattern	coffee, citrus, deciduous fruit
2. hedged crops	tea
3. thick stands of natural and exotic trees with little to no grass cover	forestry
D. Grasslands	
1. stoloniferous grasses planted in rows from runners; permanent pastures	star, Kikuyu, torpedo
2. seed established grasses usually broadcast; bunch varieties	love grass, Sabi panicum, Katambora Rhodes, Giant Rhodes
3. species composition closely related to the natural regions soil types and condition of the veld	natural veld grasses, usually mixed species predominantly bunch grasses, both annual and perennial

Source: Elwell and Stocking 1976.

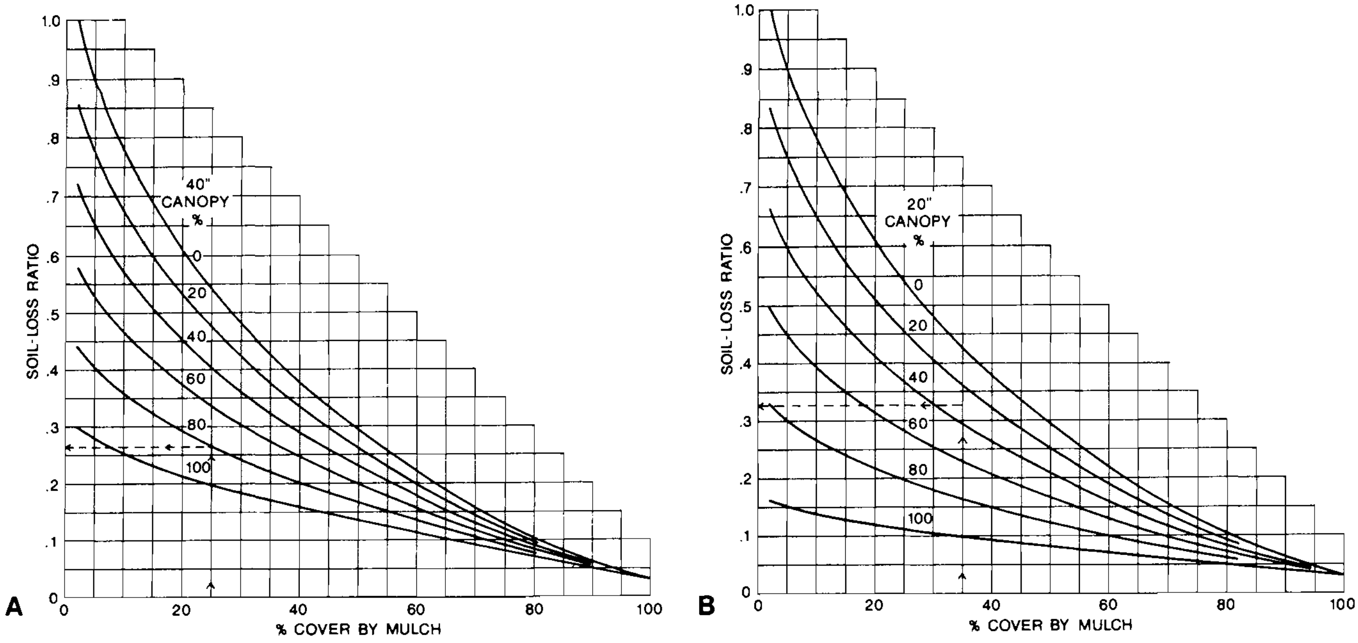


Figure 28. Combined mulch and canopy effects when average fall distance of drops from canopy to the ground is about (A) 1 m; (B) 0.5 m. (Wischmeier and Smith 1978)

Terraced farming has been tried in Africa, but generally has failed because the terraces have broken down. This system seems to work well only in densely populated areas such as those in Asia where sufficient labor is available to maintain and repair terraces. Similarly, Thomas (1967) observed that only in the densely populated areas of Africa and Asia will people make the effort to spread manure on crops.

Shifting cultivation is an important aspect of tropical agriculture and has a profound effect upon the land (Nye and Greenland 1960; Watters 1971). About 30 percent (36 million km^2) of the world's exploitable soils, involving 200 to 250 million people, were reported as farmed in this manner (Hauck 1974; Lal 1974). It is known variously as slash and burn, *kaingin,* bush fallowing, milpa, *ladang,* patch, *agricultura nomada,* swidden, and other terms. A general definition of shifting cultivation is "any system under which food is produced for less than ten years from one area of land, after which that area is abandoned temporarily and another piece of land cultivated. The houses of the cultivators may or may not be abandoned when the land itself is abandoned; usually they are not." Abandoned land is recultivated after the fertility of the land is judged to be restored (Greenland 1974). In shifting cultivation a variety of crops are planted in the land area cleared by the cultivator. Sometimes as many as twenty species are planted at the same time, which generally means that the soil is fairly well protected from the erosive action of rainfall. The main difficulty with the system is that burgeoning populations have continually caused the fallow period to become shortened below the period necessary for restoring the soil to its former productivity level. Various ratios have been recommended for crop:fallow periods, such as 1:5 in Venezuela. In other sections of Latin America there is still much experimentation to find a proper ratio (Watters 1971). Whether shifting cultivation degrades the soil or not is a controversial question. Aside from the hazards associated with the areas cleared intentionally for cultivation, uncontrolled burning of forests has been cited as a cause of serious erosion (Lal 1974). Thomas (1967) provided an interesting description of African farms under shifting cultivation; To the European or North American, accustomed to neat and orderly fields of crops, such a farm presents a bizarre appearance in the forest. There is a great diversity of crops such as coffee, cocoa, banana, taro, and yams or if the soil is poor cassava and sweet potatoes. Helter-skelter as this system appears, it is a wise one as regards erosion-protection for each crop is gathered when ready. Thus enough cover is left to protect the soil from the drying effects of the sun and the erosive power of rain. Additional evidence exists to support shifting cultivation although many regard it as a primitive and inefficient system (FAO 1957). Interestingly, it appears that no general intensive method

Table 52. Soil loss ratios (percent) for final cropstage (harvest to plowing) when stalks are chopped and distributed without soil tillage

Mulch cover*	Corn or sorghum		Soybeans		Grain stubble§
	Tilled seedbed†	No-till	Tilled seedbed†	No-till in corn residue‡	
20	48	34	60	42	48
30	37	26	46	32	37
40	30	21	38	26	30
50	22	15	28	19	22
60	17	12	21	16	17
70	12	8	15	10	12
80	7	5	9	6	7
90	4	3	--	--	4
95	3	2	--	--	3

Source: Wischmeier and Smith 1978.
* Percentage of a field surface directly covered by pieces of residue mulch;
† This column applies for all systems other than no-till;
‡ Cover after bean harvest may include an appreciable number of stalks carried over from the prior corn crop;
§ For grain with meadow seeding, include meadow growth in percent cover and limit grain period 4 to 2 months. Thereafter, classify as established meadow.

Table 53. P factor for conservation practices in West Africa

Conservation practices	P factor
Tied-ridging	0.20-0.10
Antierosive buffer strips from 2 to 4 m width	0.30-0.10
Straw mulch	0.01
Curasol mulch (60 g/l/m^2)	0.50-0.20
2-3 years of temporary grassland	0.5-0.1
Reinforced ridges of earth or low dry stone walls	0.1

Source: Roose, 1977c.

of mechanical agriculture has been found in the tropics to supplant the old style requiring only a digging stick and fire (Seavoy 1975). Belgian agronomists attempted to establish continual agricultural production in the Congo (now Zaire) to replace shifting cultivation. The system failed (Eckholm 1976).

Changes in soil productivity associated with land use after clearing have been evident but not well investigated. Soil structure deterioration begins as soon as the cycle of shifting agriculture begins. First, grass, bush, and forest trees are removed from the land to be cultivated. Mechanical removal and removal by burning of organic material from the soil surface sets the stage for soil structure deterioration and leaching of (originally recyclable) plant nutrients by rainwater. Nutrients supplied by decomposing plant remains lead to a brief fertility increase in the first year or two, after which a downward trend ensues due to leaching and removal of nutrients by crops. Allan (1965) illustrated such a trend. As the structure of the soil further deteriorates and weakened crops provide less vegetal cover each year, the danger of soil loss increases. The period of cultivation may range from one to a dozen or more years. When yields fall below the minimum level required for subsistence, the land is returned to fallow and is allowed to replenish its fertility under bush or forest vegetation. As the pressure on the food supply increases the level of subsistence return drops; that is, lower yields are acceptable and cultivation periods lengthen. An example from the Tiv area in Nigeria

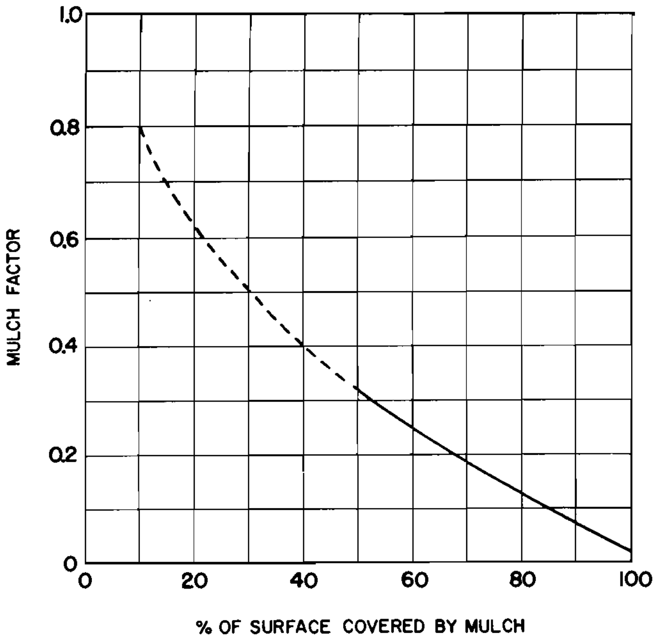


Figure 29. Effect of plant residue mulch on soil loss. Mulch factor is the ratio of encountered soil loss to corresponding loss without mulch. (Wischmeier 1973)

illustrates this problem. In this region, covering approximately 26,000 km^2 and supporting a population of 900,000 people, some of the more heavily populated areas (with more than 154.4 persons per km^2) are showing a reduction in the fallow period (Vermeer 1970). Lands once fallowed for ten years now rest for only two. Declining yields have led to a longer "hungry season" at the end of the crop year and a movement away from yam production (yams require relatively more fertile soil for success) toward small grain production. Each year, more land goes out of production as fertility declines and erosion strips the soil and exposes underlying rock.

A major change in land use patterns in the tropics is that already, in places, the fallow periods of the shifting cultivation cycle have been abandoned altogether. This is happening at a time when the resource and technological inputs required to sustain agricultural production on cleared lands are ill defined. Continuous cultivation on moderately sloping land of an agricultural experiment station at Serere, Teso district, Uganda led to such intense erosion that in ten years the land had to be abandoned. Nearby soils of a similar erosion-resistant nature, suitable for permanent or semipermanent cultivation, showed only "a relatively small drop in soil productivity over twenty years" when two years of natural fallow followed three cropping years (Allan 1965). The acreage affected by reduced fallow periods and the impacts on productivity loss due to this reduction are not known even approximately. An American official with USAID has, as quoted from Eckholm (1976), "suggested that crop yields are declining 'in wide areas of Volta, the Guinea Coast, Zambia, Malawi, and Madagascar'." Eckholm continued with the observation that per capita food production in Africa has declined over the last twenty years.

The reason for yield declines under shifting cultivation are not entirely clear. An analysis of the properties of some Zambian soils led Ballantyne (1958), reported by Allan (1965), to conclude that loss of soil structure accounted for grain yield declines under shifting agriculture. Lal (1976*c*) has shown that soils commonly used in shifting agriculture suffer reduced infiltration, change in surface texture from finer to coarser, and reduced moisture-retention capacity with consecutive cropping. He hypothesized that soil erosion is the cause of these deteriorating characteristics. Reduced soil fertility is a generally accepted reason for yield declines and was illustrated by Ofori (1974). Hudson and Jackson (1959) have shown a direct relationship between soil loss and crop production (Fig. 19). See chapter 3 for additional information on erosion-productivity relationships.

Wild Lands

Forests, grazing areas, and other uncultivated lands, which often are in steep terrain, are termed "wild lands." When these are situated at the upper

Table 54. P values and slope-length limits for contouring

Land slope (%)	P value	Maximum length* (ft)
1 to 2	0.60	400
3 to 5	.50	300
6 to 8	.50	200
9 to 12	.60	120
13 to 16	.70	80
17 to 20	.80	60
21 to 25	.90	50

Source: Wischmeier and Smith 1978.
*These values may be increased by 25 percent if residue cover after planting will regularly exceed 50 percent.

Table 55. P values, maximum strip widths, and slope-length limits for contour strip-cropping

Land slope (%)	P values A*	P values B†	P values C‡	Strip width§ (ft)	Maximum length (ft)
1 to 2	0.30	0.45	0.60	130	800
3 to 5	.25	.38	.50	100	600
6 to 8	.25	.38	.50	100	400
9 to 12	.30	.45	.60	80	240
13 to 16	.35	.52	.70	80	160
17 to 20	.40	.60	.80	60	120
21 to 25	.45	.68	.90	50	100

Source: Wischmeier and Smith 1978.
* For 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it.
† For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow.
‡ For alternate strips of row crop and small grain.
§ Adjust strip-width limit, generally downward, to accommodate widths of farm equipment.

Table 56. P values for contour-farmed terraced fields*

Land slope (%)	Farm planning: Contour factor†	Farm planning: Strip-crop factor	Computing sediment yield‡: Graded channel sod outlets	Computing sediment yield‡: Steep backslope underground outlets
1 to 2	0.60	0.30	0.12	0.05
3 to 8	.50	.25	.10	.05
9 to 12	.60	.30	.12	.05
13 to 16	.70	.35	.14	.05
17 to 20	.80	.40	.16	.06
21 to 25	.90	.45	.18	.06

Source: Wischmeier and Smith 1978.
*Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contouring factor is used in the computation.
†These values may be used for control of interterrace erosion within specified soil-loss tolerances.
‡These values include entrapment efficiency of the catchment (see chap. 2A) and are used for control of offsite sediment within limits and for estimating the field's contribution to watershed sediment yield.

parts of river basins they will greatly affect water flow in the lower parts of the streams and rivers (Kunkle and Harcharik 1977). The highly beneficial effects of forests on controlling runoff are well documented (Bennett 1939; Kohnke and Bertrand 1959; Ahmad and Breckner 1974; Patric and Brink 1977). For example, in a comparative watershed study in Kenya, in which 76 mm of rain fell in 30 min at a maximum short-duration intensity of 254 mm/hr, it was found that a 32 ha housing development produced a flow of 2.15 m^3/sec through a flume installed in a grassed waterway. The peak rate through a similar installation in the adjacent forest watershed of similar area was only 0.056 m^3/sec, almost forty times lower (Pereira 1973). Infiltration rates are significantly higher in forests than in comparable agricultural or pastoral areas. In a Russian study, hardwood forests were found to have roughly six to twenty times higher infiltration rates than ploughed land (Molchanov 1963, cited by Kunkle and Harcharik 1977). In a tropical environment, a Hawaiian study of forestland versus adjacent agricultural land (pineapple, sugarcane) or pasture showed that 14 of 15 sites had much higher infiltration rates in the forest plots (1.2 to 500 times) than their counterparts under agriculture or pasture (Wood 1977). The same author reported that forested soils had greater porosities and less erodible aggregates than the non-forest-covered soils. In Nigeria, even in secondary forest (bush fallow), much higher infiltration capacities (horizontal plus vertical infiltration) were found when compared to such land after a year in crops. This was attributed, at least in part, to horizontal channels formed by the activity of ants and earthworms in the surface horizons of the forest soils, which disappeared after cultivation (Wilkinson and Aina 1976).

The valuable contribution of forest litter has also been realized by conservationists (Bennett 1939). Most importantly the twigs, mold leaves, stems, and bark fragments that comprise the litter act as a barrier to protect the pores and channels into which rainfall may infiltrate (Lowdermilk 1936, cited by Bennett 1939). In the presence of such protection, destructive effects of raindrop impact and formation of soil surface seals are unlikely. Secondarily, this ground cover serves as a sponge or blotter that absorbs and holds rainfall. However, this function is not considered as important as the safeguarding of soil pores against sealing and thus maintaining high infiltration rates and reducing runoff. Litter also contributes to slowing down the surface movement of runoff, thus allowing good water infiltration during longer contact with the soil. The surface of undisturbed forest soils is characterized by a thick, organic-matter layer with considerable biotic activity (Bates 1960). The organic matter fraction of soils has been correlated with aggregate stability (Baver 1968; Greenland 1971). Thus, a long-term benefit of rich forest litter is that it favors aggregate stability, a factor which earlier was shown to be strongly correlated with soil erodibility (El-Swaify and Dangler 1977).

At least half of the wood cut in the world each year is burned for fuel. Eckholm (1976) referred to this as "the other energy crisis." It is becoming increasingly difficult for people in India, Africa, Asia, and Latin America to obtain wood for fuel. For example, in Ougadougou, Upper Volta, 20 to 30 percent of a laborer's income is spent on firewood. A circle of 70 kilometer radius from Ougadougou has been denuded of trees by the the inhabitants of this city—and the circle is expanding (Eckholm 1976). The greatest scarcity of wood exists on the Indian subcontinent, where, as an alternative, many rural inhabitants use handmolded dung patties for fuel. This practice is rapidly spreading and subsequent loss of the major source of organic fertilizer is assured. Consequently the impoverished soils are further degraded (Eckholm 1976).

In the Philippines, at the peak of the dry season, vast areas of pasture are burned by ranchers in an attempt to eliminate the unpalatable (to cattle) old cogon *(Imperata cylindrica)* and to provide young growth for forage. When the rainy season commences, surface cover is scanty and erosion is thus enhanced. Furthermore, burning actually favors the establishment of *Imperata cylindrica* over other forage grasses. In the Ilocos region of the Philippines there is an unusual demand for fuel to cure tobacco. Tree cutting is intensive, so that in this mountainous region erosion is accelerated (Weidelt 1975).

Shifting cultivation is one of the main sources of deforestation in Thailand, resulting in increasing soil erosion (de Boer 1977). In Sabah, logging roads are established with a minimum of earthwork and slope gradients are disregarded; gradients of nearly 30 degrees are not uncommon. There is no attention to drainage by use of culverts or keeping the water on the inside of the road. Thus, erosion goes on during logging as well as for years afterwards. Ultimately, whole sections of roads slip and lead to formation of gullies (Burgess 1971). With the land rush on in Sabah there is growing concern that the forest will disappear as seems to be the fate of the lowland Dipterocarp forest in Peninsular Malaysia (Chim and Soon 1973).

Construction Activities

Poorly planned construction, whether for homes, factories, roads, or shopping centers, may cause serious erosion problems. The major difficulty results from the removal of the vegetative cover and topsoil, which impairs infiltration and favors runoff from rainstorms. For example, the construction of homes on what had been farmland in Kensington, MD resulted in 168 Tm/ha (75.6 tons/acre) soil loss per year (Guy 1965). A 2.65 km (1.65 mile) long logging road caused an increase of 250 times the sediment in runoff during the first storm following construction, in comparison to an adjacent watershed (Fredericksen 1965). In Tama New Town, which is a very large housing subdivision near Tokyo, (1200 mm annual rainfall) 15.4 mm/yr of soil were lost from loam and sand layers. After completion of pavements, drainage ditches, and the establishment of cover, the sediment yield approached zero (Kinoshita and Yamazaki 1975). A comparative study in the metropolitan area of Washington, DC in the United States showed that soil losses from construction sites varied from 100–500 Tm/ha/yr in contrast to soil losses of 3–7 Tm/ha/yr from nonconstruction areas (Chen 1974). Similarly, sediment loads in a stream from an area undergoing urbanization near Ottawa, Canada were 3 to 5 times as great as those from a neighboring rural area (Warnock and Lagoke 1974). Sediment yield was 91 Tm/ha during construction of an office complex over a two year period in Reston, VA. An adjacent forested area yielded negligible sediment. It was also found that installation of paved streets, parking lots, and buildings by no means reduced sedimentation proportionately. Increased runoff was considered to cause greater erosive power on the channel system (Guy 1974).

Ateshian (1974) found that an average of 31.3 percent of the total annual sediment from roadbanks was produced by the largest storm. However, for highway design work it has been pointed out that more reliable estimates of sediment yield may be made on a yearly or monthly basis than from individual storms (Diseker and Sheridan 1971).

An additional study of river sediments on the Coastal Plain and Piedmont areas of Maryland (Wolman and Schick 1967) indicated that sediment concentrations from construction areas ranged from 3000 to over 150,000 ppm; in agricultural catchments the highest concentration of suspended sediments was only 2000 ppm. In terms of annual loss this represents a maximum of approximately 500 Tm/ha/yr from construction sites. Road cuts in Georgia (Wolman and Schick 1967) produced comparable losses of roughly 180 to 490 Tm/ha/yr and surface losses of 3 to 6 cm from the road cuts in less than one year.

No quantitative information on the contribution of construction activities was available for developing tropical countries. However, the data presented above would indicate inevitable serious losses of soils during such activities whenever protective precautions are not followed. The extent and duration of disturbance associated with a specific construction activity will determine whether the magnitudes and impacts of resulting losses are as important as those affecting farms and wild lands.

CHAPTER 5
EROSION CONTROL MEASURES

From the discussion of the causative factors of soil erosion in chapter 4, it is evident that several factors are subject to manipulation, a fact which provides the basis for erosion control. Among the parameters of the USLE, controllable parameters include primarily C (crop management), P (support practices), and LS (topography). While the soil susceptibility parameter (K) is generally presumed constant and inherent to the soil, it too can be changed by any means that alter soil structure. Such alteration is commonly achieved by tillage and amendment management practices such as in the reclamation of sodic soils.

Absolute prevention of soil erosion is unattainable and often unnecessary; therefore a realistic goal is to keep soil losses within "tolerable" limits as defined in chapter 1. If this can be achieved throughout the tropics, a major step will have been taken toward alleviating critical world food shortages and reducing the frequently calamitous effects of erosion discussed in chapter 3.

Conservation has come to mean the wise use of resources. Given that, according to a widely used estimate, a foot of soil generally requires more than a thousand years to form, limiting soil losses is mandatory if future human generations are to survive. We must learn to blend our land use more harmoniously with the environment, as the recent concern with ecology has taught us. We are rapidly running out of new locations of arable land. With the human population expected to double by the early part of the twenty-first century, we must conserve (wisely use) existing soil resources and limit the exponential population growth. While the latter problem must be solved by other disciplines, dwindling soil resources and soil productivity are our problem. Herd sizes exceed the carrying capacity of the land in many developing nations; vast tracts of timber are clear-cut and logging roads are built without regard to ecological consequences, especially in Southeast Asia; shortened fallow periods in shifting cultivation render that practice little more than intensive agriculture without the inputs required for sustained productivity; emigration is followed by resettlement on fragile soil systems which require careful management to support agricultural crops, as appears to be evident in Amazonia and Indonesia; throughout the tropics wholesale destruction of woody plants to obtain firewood leads to removal of cover. The list goes on. All result in ever-increasing soil losses.

The first step in a conservation plan should be an inventory and classification of lands for their best possible use. Such a plan should recognize the limitations and constraints that may have to be considered to use a particular land area wisely. The land capability concept was first developed in the United States (SCS 1948; Klingebiel and Montgomery 1961), but physical and socioeconomic conditions are so different in the tropics that the U.S. classification is not relevant—either to most lesser developed countries (LDCs), or to excessively steep slopes anywhere. Erosion risk assessment should be recognized as an integral part of land classification (Blair-Rains 1981, Douglas 1981, Bennema and De Meester 1981). "Sheng's scheme of land capability classification for Jamaica" (Sheng and Stennett 1975) serves as a model for developing countries, especially those with predominantly hilly land (see Table 57). Preparation of such a classification is a first step. If land use is planned so as to conform either to this classification or a similar one, many erosion problems could be avoided at the outset and later minimized. In the words of the proverb, "An ounce of prevention is worth a pound of cure." The basic principles of erosion control involve the dissipation of raindrop impact which limits soil detachment and favors water infiltration, and reduction of runoff volume and velocity which diminish sediment transport. Much of this can be achieved on cultivated lands by enhancing the concepts of good

Table 57. Sheng's scheme of land capability classification for Jamaica --a treatment-oriented scheme especially for hilly watersheds

Slope / Soil depth	1. Gently Sloping <7°	2. Moderately sloping 7° - 15°	3. Strongly sloping 15° - 20°	4. Very strongly sloping 20° - 25°	5. Steep 25° - 30°	6. Very Steep >30°
Deep (D) > 90 cm	C_1	C_2	C_3	C_4	FT	F
Moderately deep (MD) 50-90 cm	C_1	C_2	C_3	C_4 / P	FT / F	F
Shallow (S) 20-50 cm	C_1	C_2 / P	C_3 / P	P	F	F
Very shallow (VS) <20 cm	C_1 / P	P	P	P	F	F

Source: Sheng and Stennett 1975.

1. Symbols for most intensive tillage or uses:

   C_1 Cultivable land 1, up to 7° slope, requiring no, or few, intensive conservation measures, e.g. contour cultivation, strip cropping, vegetative barrier, rock barrier, and in larger farms, broadbase terraces.

   C_2 Cultivable land 2, on slopes between 7° and 15°, with moderately deep soils needing more intensive conservation e.g. bench terracing, hexagon, miniconvertible terracing for the convenience of four wheel tractor farming. The conservation treatments can be done by medium sized machines such as Bulldozer D5 or D6.

   C_3 Cultivable land 3, on slopes from 15° to 20°, needing bench terracing, hexagon, and miniconvertible terracing on deep soil and hillside ditching, individual basin on less deep soil. Mechanization is limited to small tractor or walking tractor because of the steepness of the slope. Terracing can be done by a smaller tractor with 8 ft wide blade.

   C_4 Cultivable land 4, on slopes of 20° to 25°; all the necessary treatments are likely to be done by manual labor. Cultivation is to be practiced by walking tractor and hand labor.

   P Pasture, improved and managed. Where slope approaches 25° and when the land is too wet, zero grazing should be practiced. Rotational grazing is recommended for all kinds of slopes.

   FT Food trees or fruit trees. On slopes of 25° to 30°, orchard terracing is the main treatment supplemented with contour planting, diversion ditching, and mulching. Because of steepness of slopes, interspaces should be kept in permanent grass cover.

   F Forest land, slopes over 30°, or over 25° where the soil is too shallow for any of the above soil conservation treatments.

(Continued)

Table 57. (Continued)

2. Any land which is too wet, occasionally flooded, or too stony, which prevents tillage and treatment, should be classified as:

   (a) Below 25° -- Pasture
   (b) Above 25° -- Forest

3. Gully dissected lands which prevent normal tillage activities--Forest.

4. Mapping Symbols: might be labeled as:

   $$\frac{\text{Most intensive use}}{\text{soil-slope-depth}}$$

   example: $$\frac{C_2}{32 - 2 - D}$$

   means: $$\frac{\text{Cultivable land 2}}{\text{wirefence clay loam - } 7^\circ \text{ to } 15^\circ \text{ - 36 in}}$$

   Or, it could be simply labeled as C_2.

land husbandry which favor high productivity as well (Shaxon 1981). When supported by a realistic land capability classification, implementation of these concepts can provide a safeguard against severe soil erosion.

There are many ways to classify erosion control practices but for our purposes the primary breakdown will be into *traditional* for the localized methods employed largely in the LDCs and *developed* to indicate more universal practices.

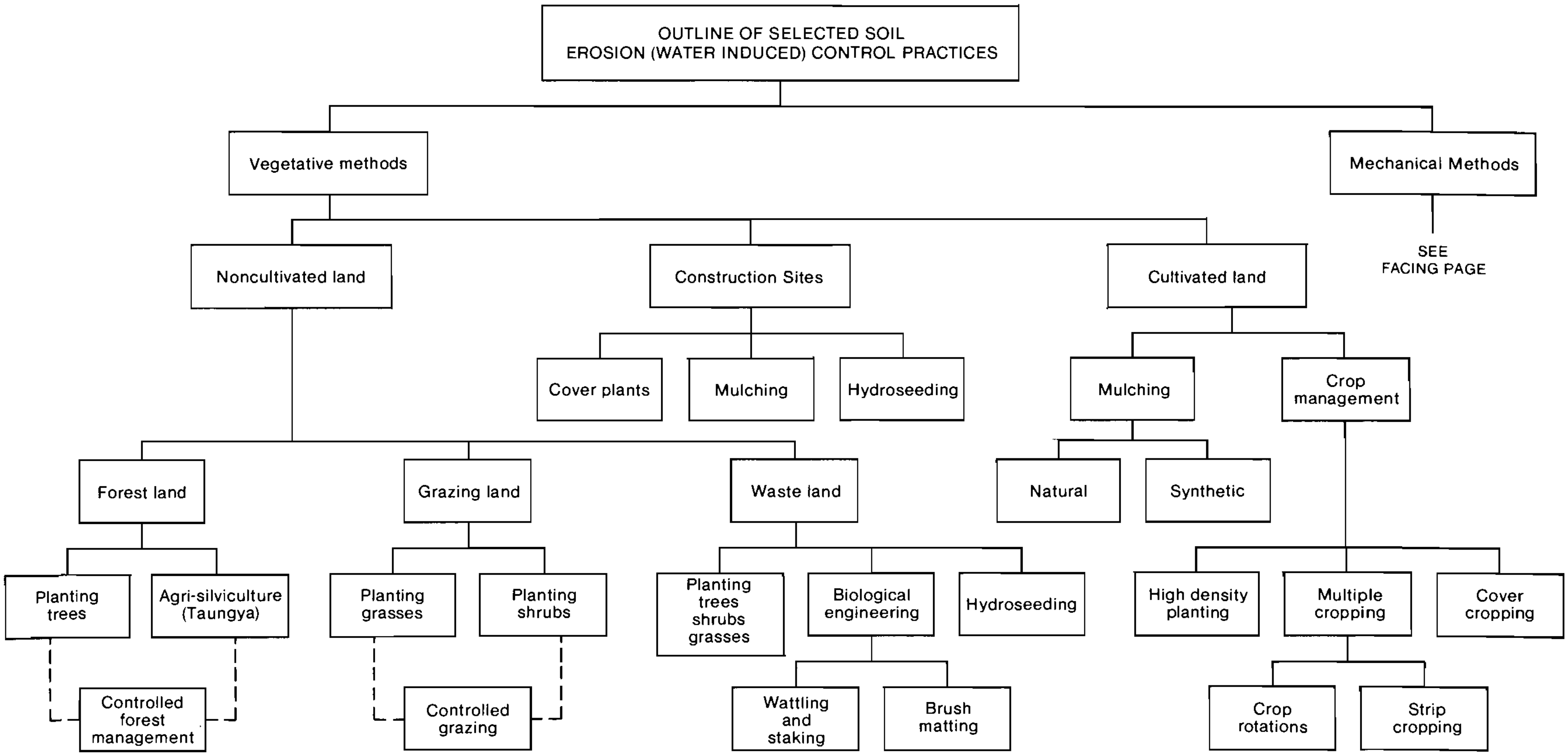
TRADITIONAL SYSTEMS

Some successful forms of erosion control are unique to certain areas. For example the "lock and spill" technique is traditional in Sri Lanka. In this method a fairly deep runoff storage ditch is constructed at the base of the field, with a berm placed downslope of the ditch. Runoff is stored in the basin and eventually evaporates or infiltrates into the soil. On pineapple plantations in Hawaii it is customary to position and secure large plastic sheets on small falls in the waterways to prevent undercutting and downcutting—a practice that works quite well as long as the gradient is not excessive. A seemingly clever erosion control practice in Ecuador has been reported verbally by Dr. D. Plucknett of the World Bank staff: Two bunds are constructed up and down slope. The area between is shaped into small ridges that wind in a serpentine manner down the hillside. Runoff water is thus confined laterally by the bunds and progresses relatively slowly downslope behind the barriers made across the slope by the ridges. Undoubtedly other erosion control procedures exist that are as yet generally unknown outside the country or area in which they are practiced. Such techniques represent a potentially valuable conservation resource and when recognized should be made more universally available. Sophisticated terracing systems have been built by early civilizations in many countries (e.g. in South America and the Philippines); many are still in use today.

DEVELOPED SYSTEMS

A number of erosion control practices are used throughout the world in developed countries and increasingly in LDCs (Fig. 30).

Vegetative measures (such as mulching, use of cover crops, strip-cropping, and the like) all favor maintenance of good rainfall infiltration into soil, whereas heavier mechanical operations (including land-shaping, construction of waterways, contour bunds, terraces, or ridges) are based on reducing topographic hazards and safe removal of runoff. Both have feasibility limits. Very often, application of both kinds of measures is necessary for a sound conservation program (Lal 1977*b* and 1981). In the following pages various erosion control measures will be discussed in broad terms. Specifications and detailed design criteria may be obtained from pertinent technical sources such as the Soil Conservation Service (1975*a*), publications of the Food and Agricultural Organization of the United Nations,


OUTLINE OF SELECTED SOIL EROSION (WATER INDUCED) CONTROL PRACTICES
Vegetative methods
Mechanical Methods
SEE FACING PAGE
Noncultivated land
Construction Sites
Cultivated land
Cover plants
Mulching
Hydroseeding
Mulching
Crop management
Forest land
Grazing land
Waste land
Natural
Synthetic
Planting trees
Agri-silviculture (Taungya)
Planting grasses
Planting shrubs
Planting trees shrubs grasses
Biological engineering
Hydroseeding
High density planting
Multiple cropping
Cover cropping
Controlled forest management
Controlled grazing
Wattling and staking
Brush matting
Crop rotations
Strip cropping

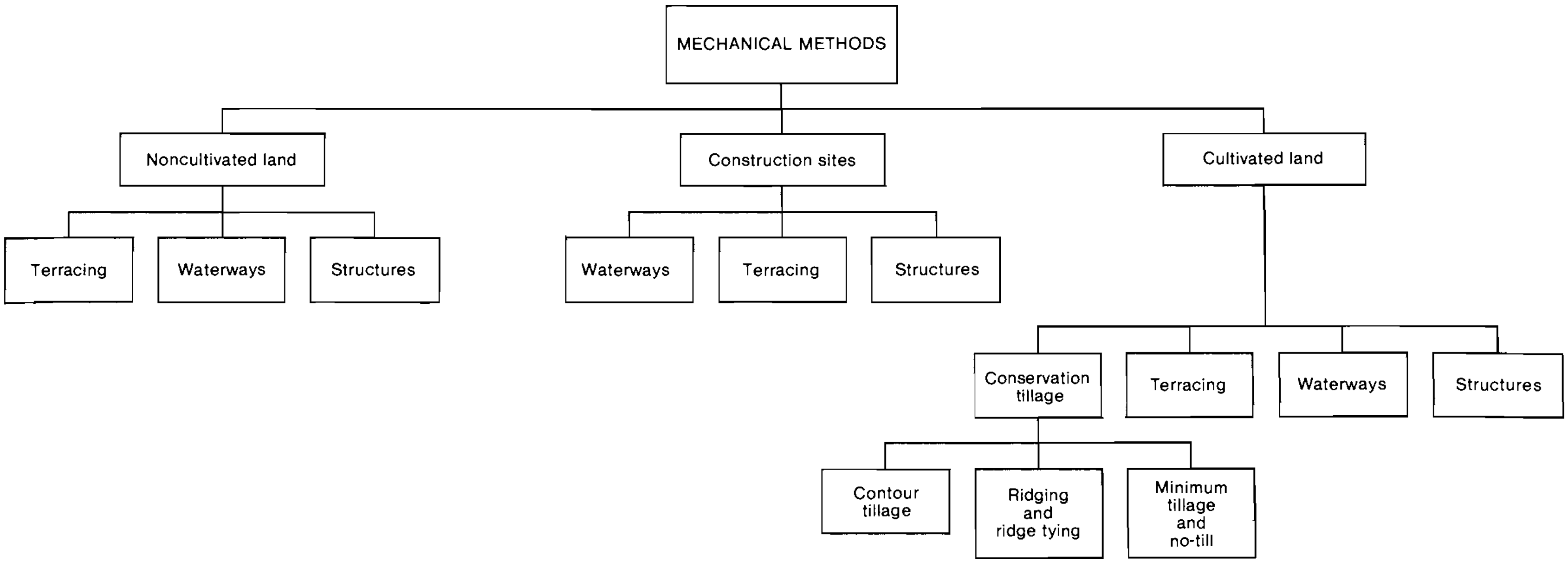


Figure 30. Flow chart of selected soil erosion practices for water-induced soil erosion.

other engineering manuals (Hudson 1975; Beasley 1972), the Manual of Reforestation and Erosion Control for the Philippines (Weidelt 1975), and/or from experienced field conservationists. The problems and practice of soil conservation were the subject of a recent conference and subsequent published proceedings (ICSC 1981).

Vegetative Control Methods

Vegetation is the key to the prevention of soil erosion (see chapters 2 and 4). If all soils were perpetually covered with mature forests or grass sward, accelerated erosion would not be a problem. However, at least for brief periods of time, farming, logging, fires, mining, and construction activities expose the soil, which then becomes vulnerable to erosive rainfall and runoff. In Table 58 are listed all the plant species discussed in this chapter as well as others, that have been found useful for erosion control.

Noncultivated Lands

Forest Land. Several attributes of natural forest vegetation are responsible for the effectiveness of forests in protecting the soil against erosion. In the humid tropics these include the appreciable soil protection by the canopy and undergrowth, little soil exposure due to abundant litter and minimum disturbance, beneficial soil binding by highly proliferated roots and decomposed organic matter, and the frequently significant activity associated with the presence of earthworms or other soil fauna. Coupled with the high evapotranspiration demand of forest vegetation, these attributes can minimize soil detachment and maximize infiltration rates thus providing restricted runoff and erosion (e.g. Lal 1980, Sanchez 1976).

Verduzco (1960) recommended that each country keep at least 25 percent of its land area in forests. This general statement was prompted by the occurrence of floods, droughts, dust storms, erosion, and sudden temperature changes in Mexico following the destruction of forests in that country. In light of the Mexican experience, it is unfortunate that herbicides were used to defoliate and thus destroy large areas of jungle in South Vietnam (Maher 1972). Interestingly, however, Budowski (1956) claimed that there is no evidence to uphold the belief that a soil may become too poor to support forest regrowth in tropical regions.

The illustrations that follow show how some developing countries have incorporated tree planting in reforestation or afforestation programs intended primarily to curtail or correct erosion problems.

Example 1—India: Afforestation of a badly eroded and gullied 272 ha area at Rehmankhera has been reported (Jalote and Malik 1974). Initially, fencing was installed to keep livestock out. Then soil trenches 180 by 60 by 45 cm deep were dug, in which seeds of *Dalbergia sissoo, Acacia nilotica, Acacia catechu, Ailanthus excelsa,* and *Albizia lebbek* were sown. Nursery transplants supplemented the seeding. The project was started in 1951–1952 and reforestation was completed in 1964. Today complete cover exists and the soil is well protected.

Example 2—Malagasy Republic: Retimbering degraded lands is ongoing in the Malagasy Republic (Madagascar). Various *Eucalyptus* species are favored and 130,000 ha of high land have been planted with these fast growing trees. Pine plantations have been established on 16,000 ha, three quarters of which are located in the Matsiatra Valley. In addition 4000 ha of land around Lake Alaotra have been sown from the air with *Mimosa* spp., Dingadingana (scientific name unavailable), and others to protect the watersheds (Le Bourdiec 1972).

Example 3—The Philippines: Different objectives may have governed the planting of forests in the Philippines. Only eight species of sawtimber are recommended, as too many species were presumed to cause marketing problems. The eight are large-leaf mahogany *(Swietenia macrophylla),* teak *(Tectona grandis),* benguet pine *(Pinus insularis),* narra *(Pterocarpus indicus),* prickly narra *(Pterocarpus vidalianus),* melina *(Gmelina arborea),* kariskis *(Albizia falcataria),* and bagras *(Eucalyptus deglupta).* Four of these species—benguet pine, melina, kariskis, and bagras—are also recommended for pulpwood plantings. Ipil-ipil *(Leucaena leucocephala)* is the commonest fuelwood in plantations, although kakawati *(Gliricidia sepium)* and Cassia siamea are also planted for this purpose (Weidelt 1975).

Example 4—Bolivia: In South America, Chase (1976) has suggested that algaroba (*Prosopsis* spp.), carob *(Ceratonia siliqua)* and honey locust *(Gleditsia triacanthos)* be used for forest farming in Bolivia. All bear pods that contain 16–21 percent protein and the meal is an excellent food source for cattle and suitable for human consumption as well. Their es-

Table 58. Selected vegetation useful for erosion control*

Acacia catechu -- Acacia, Catechu, Cutch tree, Khair

Acacia decurrens -- Black, silver, or green wattle

Acacia mangium -- N.A.†

Acacia nilotica -- Acacia, gumarabic, babul, suntwood

Acacia tortilis -- Gummi-akazie

Acioa barteri -- N.A.

Aeschynomene indica -- Joint vetch

Agave cantala -- Maguey

Ailanthus excelsa -- Ailanthus

Albizia falcataria -- Kariskis

Albizia lebbek -- Woman's tongue tree, Lebbek tree, Siris tree

Alnus maritima -- Japanese alder

Alternanthera brasiliana -- Racaba

Alysicarpus rugosus -- Alyce clover

Arachis hypogaea -- Groundnut, peanut

Arundinella nepalensis -- N.A.

Astragalus garbancillo -- Milkvetch

Avena sativa -- Oats

Axonopus compressus -- Carpet grass

Bambusa spinosa -- Bamboo, Kawayan

Bambusa vulgaris -- Bamboo, Kawayan-Kiling

Bothriochloa intermedia --Australian bluestem

Brachiaria decumbens -- N.A.

Bromus spp. -- Brome grass

Broussonetia papyrifera -- Paper mulberry

Cajanus cajan -- Arhar, pigeon pea, Congo pea, etc.

Calamagrostis spp. -- Reed grass

Calliandra callothyrsus -- N.A.

Calligonum spp. -- Calligon

Calopogonium caeruleum -- Calopogonium, jicuma

Calopogonium mucunoides -- Calopo, Calopogonium, Katjang asoe

Cassia hookeriana -- Shower tree

Cassia siamea -- Kassod tree

Cenchrus ciliaris -- Sandbur

Cenchrus sitigerus -- Sandbur

Centrosema pubescens -- Peaflower

Ceratonia siliqua -- Carob

Chloris barbata -- Chloris

Chloris bournei -- Chloris

Chloris guyana -- Rhodesgrass

Coffea spp. -- Coffee

Crotolaria spp. -- Crotolaria

Cymbopogon coloratus -- N.A.

Cynodon dactylon -- Bermuda grass

Cynodon plectostachyum -- Stargrass

Dactylis glomerata -- Cocksfoot, orchard grass

Dalbergia sissoo -- Sissoo

Datura alba -- Trumpet tree

Dendrocalamus strictus -- Male bamboo, Calcutta bamboo, bans, etc.

Desmodium diffusum -- Desmodium, tick clover, beggar weed

Desmodium intortum -- Desmodium, tick clover, beggar weed

Desmodium uncinatum -- Spanish clover

Dichanthium annulatum -- N.A.

Digitaria decumbens -- Pangola grass

Dolichos lablab -- Hyacinth bean, lablab

(Continued)

Table 58. (Continued)

Eragrostis curvula -- Weeping love grass

Erigeron mucronatum -- Australian daisy

Eucalyptus deglupta -- Bagras

Eucalyptus spp. -- Eucalyptus

Ficus nota -- Tibig

Gleditsia triacanthos -- Honey locust

Gliricidia sepium -- Madre de cacao, kakawati, Nicaraguan cocoa shade

Gmelina arborea -- Melina

Glysine Max -- Soybean

Halaxylon persicum -- N.A.

Helianthus tuberosus -- Mexican sunflower, girasole, Jerusalem artichoke

Homonoia riparia -- Dumanay

Indigofera endecaphylla -- Creeping indigo

Lagerstroemea subcostata -- N.A.

Lantana camara -- Yellow sage

Lasiurus sindicus -- N.A.

Lespedeza cuneata -- Lespedeza

Leucaena leucocephala -- Uaxin, koa haole, ipil-ipil, lamtoro

Lolium perenne -- Perennial ryegrass

Lupinus spp. -- Lupin

Macroptillium atropurpureum -- Siratro

Mallotus japonicus -- N.A.

Medicago sativa -- Lucerne, alfalfa

Mimosa spp. -- Mimosa

Mucuna cochinchinensis -- Velvet bean

Mucuna nigricans -- Lipai

Musa sapientum -- Banana

Nauclea spp. -- Sarcocephalus, fathead tree, West African boxwood, bengal perampocan

Neomarica northiana -- Apostle plant

Panicum maximum -- Guinea grass

Panicum turgidum -- Panicum

Paspalum notatum -- Bahia grass

Pennisetum clandestinum -- Kikuyu grass

Pennisetum pedicellatum -- Pennisetum

Pennisetum polystachyon -- Thin Napier grass

Pennisetum purpureum -- Elephant grass, Napier grass

Phalaris tuberosa -- Large canary grass

Phaseolus mungo -- Urd, black gram

Phaseolus radiatus -- Moong, mung bean, green gram

Pinus caribaea -- Cuban pine, Carib pine, slash pine

Pinus insularis -- Benguet pine

Pinus palustris -- Longleaf pine

Pinūs patula -- Tropical pine, Mexican yellow pine

Pinus rigida -- Pitch pine

Pinus taeda -- Loblolly pine

Pithecolobium dulce -- Kamachile, manella, tamarind, opiuma

Populus balsamifera -- Cottonwood

Prosopsis juliflora -- Common mesquite, algaroba

Pterocarpus indicus -- Narra, padauk, Burmese rosewood

Pterocarpus vidalianus -- Prickly narra

Pueraria javanica -- Kudzu

Pueraria phaseoloides -- Tropical kudzu

(Continued)

Table 58. (Continued)

Pueraria thunbergiana -- Kudzu vine	*Swietenia macrophylla* -- Large leaf mahogany, Honduras mahogany
Rhynchosia minima -- N.A.	*Tamarix aphylla* -- Tamarisk
Robinia pseudoacacia -- Black locust	*Tecomella undulata* -- Marwak teak
Salix spp. -- Willow	*Tectona grandis* -- Teak
Sansevieria guineensis -- Sword plant, African bowstring hemp	*Tephrosia candida* -- White tephrosia
Sansevieria zeylanica -- Ceylon bowstring	*Teramnus labialis* -- N.A.
Schizostachyum lumampao -- Boho	*Thea sinensis* -- Tea
Sesbania grandiflora -- Agati, bacule, turi, etc.	*Trifolium pratense* -- Red clover
Setaria splendida -- Bristle grass	*Trifolium repens* -- White clover
Sorghum spp. -- Sorghum	*Tripsacum laxum* -- Guatemala gamagrass, yerba Guatemala
Stizolobium deerangiana -- Velvet bean (*Mucuna deerangiana*)	*Triticum aestivum* -- Wheat
Stylosanthes gracilis -- Stylosanthes	*Urochloa Mosambicensis* -- Buffel grass
Stylosanthes guayanensis -- Stylosanthes, Brazilian lucerne	*Wedelia* spp. -- Wedelia
Stylosanthes humilis -- Stylosanthes	*Zea mays* -- Corn, maize

Source: Bunting and Milsum 1928; FAO 1977b; NAS 1979; RRIM 1977; Shankarnarayan and Magoon 1974; Weidelt 1975; and others.
*Many species are of greatest value when planted in combination with other species.
†N.A. - not available.

tablishment was encouraged since all are legumes (thus able to fix nitrogen), drought resistant, and able to fruit for a hundred years.

EXAMPLE 5—CARIBBEAN ISLANDS AND MEXICO: Development of plantation forestry is a major thrust in the government of Jamaica's watershed program. The favored species is *Pinus caribaea* (Carib pine), which is being used to restore eroded uplands and to ensure regular stream flow (Sheng and Stennett 1975). For Trinidad and Tobago, measures recommended to curtail the erosion caused by burning and shifting cultivation have been to establish such crops as limes and tonka beans at the 500 to 800 ft levels and to allow areas above 800 ft to revert to natural forest (Hardy 1942). Living fence rows (primarily willows, and cottonwoods) protect the land in Rio San Miguel, Mexico from eroding floodwaters. The living fences also serve to trap silt from the floodwaters on adjacent fields (Nabhan and Sheridan 1977).

The role of *Leucaena leucocephala* in the tropics is rapidly expanding (NAS 1977). Beside its widespread use for firewood it has value as a windbreak, as a firebreak, for charcoal manufacture, for forage, as a fertilizer source, for wood and pulp—and the apparent ability to compete successfully with cogon *(Imperata cylindrica)*. For example, on the island of Flores in Indonesia, where it is termed *lomtoro,* 10,000 ha of volcanic slopes in danger of erosion have been planted with Leucaena and 20,000 ha more were planned over the next four years (Metzner 1976). Leucaena is also being considered in the dry monsoonal areas of the Northern Territory of Australia (Walter 1971). Other rapidly growing leguminous tropical trees have great value. *Albizia falcataria* (called a miracle tree because of its exceptionally rapid growth), *Sesbania grandiflora* (forage, fuelwood, paper pulp, etc.), *Calliandra callothyrsus* (fuelwood, firebreaks, eradication of Imperata grass) and *Acacia mangium* (exceptional performance on poor sites) are among those advocated (NAS 1979).

To optimize land cultivation while at the same time preserving the valuable role of trees in hilly areas, agri-silviculture (the *taungya* system) is being used by forestry departments in some developing countries. In one form, the forest is felled and cleared by a group of farmers who then plant crops in the area. Trees are planted among the crops by forestry department personnel and the seedlings are tended by the farmers, along with their crops, for approximately two years. Subsequently, shade from the trees is enough to prevent further crop growth and the farmers are assigned new locations nearby in the forest. However, the farmers return to the old location to tend the tree crop until it can survive without care (Tempany and Grist 1958). Seventy-nine woody species and 42 agricultural crops have been listed as used in this system in the tropics (King, cited by Roche 1974). For example, taro, sweet potato, cassava, maize, and upland rice are suggested as agricultural crops to be grown in the Philippines under the *taungya* system; however banana, plantain, cassava, maize, sugarcane, rice, tobacco, and yams are not tolerated by forestry officials in some countries.

This is only one example of successful utilization of forest land with apparently minimal degradation. Similar precautions are needed whenever disturbances to natural forest are brought about by other activities such as logging and mining.

Grazing Land. A problem of great concern in developing countries is the management of livestock. The destruction of grassland by overgrazing in North Africa for example is estimated to be 100,000 ha a year (Le Houerou, cited by Semple 1971). Other examples of destructive grazing in semiarid regions have been reviewed in chapter 2. Brown (1971) speculated that cultivation can support three times the present 50 million pastoralists in Africa and suggested that these pastoralists be converted to cultivators in areas of more than 250 mm annual rainfall or where irrigation can be made available. He indicated that if such a plan cannot be worked out satisfactorily it is imperative that herd sizes be reduced. Young calves can be sent to fattening areas to reduce the load on the land. Sale of one animal enables pastoralists to feed their families on grain for six months. Semple (1971) observed, however, that destocking is not easily done because of the cultural and social values placed upon large herds, regardless of the physical condition of the animals. This latter observation was supported by Hudson (1981). Semple suggested that legumes be fostered by deferred grazing periods and by a seeding program using *Stylosanthes* spp. and *Desmodium* spp. Planned and prescribed burning was also recommended to convert worthless brushland to grassland and wooded savannahs.

Stocking rates must be realistically determined with view of both animal requirements and land capability for producing the specific pasture under consideration (Blandford 1981 and Blair-Rains 1981). Therefore, no universal formula can be given for conservation-minded use of grazing land. Harrington and Pratchett (1974), for example, suggested specific stocking rates for Ankole, Uganda, at approximately 1.1 ha per adult animal. This rate applies to rangeland largely under *Brachiaria decumbens* with unpalatable *Cymbopogon afronardus* removed (Harrington and Pratchett 1974).

Wasteland. On eroded slopes and gullies various forms of vegetative controls may be employed. The straightforward technique of planting trees, shrubs, and grasses, usually in mixtures, is one approach when the terrain is not too steep. However, as steepness increases it may be necessary to use more radical measures such as biological engineering (Figs. 31, 32). Examples of this are the various forms of brush matting or brush cover techniques. In one method sprouting or unsprouted pegs are driven in along the contour to about 20 cm deep. Sprouting brushwood is spread over the slope, butt (thicker) ends downslope, leaving no uncovered areas. The pegs are then connected with wire and driven further into the ground, pressing the brushwood firmly to the ground. A modification of brush matting is for the brushwood to be placed on small platforms or benches on the slope with the wood covered by soil from the adjacent uphill bench. Fertilizer is mixed in as well (Weidelt 1975). According to Weidelt the brush matting method, in one of its many forms, is probably the most stable of all live structures and is recommended for steep slopes, unstable soils, and

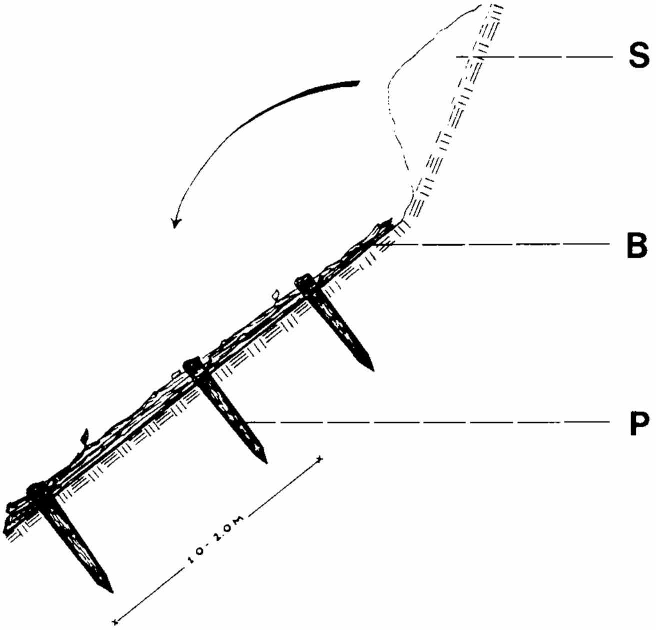


Figure 31. The brush matting technique. S = soil; B = brushwood; P = peg. (Weidelt 1975)

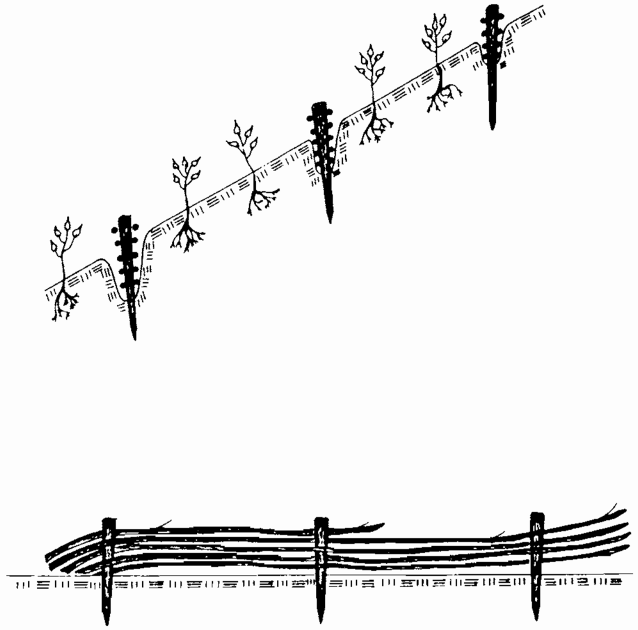


Figure 32. The wattling and staking technique. *a.* Cross section; *b.* side view. (Weidelt 1975)

high intensity rainfall areas such as the typhoon belt in the Philippines.

Another form of biological engineering is the wattling and staking method (Sheng 1977*b*; Weidelt 1975). It is used, for example, on road-fill banks and slopes in Jamaica and the Philippines. The technique used in the Philippines requires shallow trenches with stakes driven into the trenches about 50 to 70 cm apart. Wattling consists of straight rods from such plants as Leucaena or sunflower interwoven between the stakes with the butt ends of the rods bent into or covered with soil. As practiced in Jamaica, this method is more like the brush matting technique. In either case, however, grasses or trees may be planted in the bare areas between the wattles.

Hydroseeding or hydromulching is another form of vegetative control that has gained considerable popularity in the past decade. A slurry or suspension is prepared of seeds and/or stolons of grasses, plus a mulch or binder, fertilizer, and water. Application of the suspension on bare slopes can be done from back sprayers or tank trucks. Weidelt (1975) has reported that even inaccessible areas in Japan have been hydroseeded successfully from helicopters. In any case a grass cover is provided to slopes both quickly and conveniently. This technique is widely used for stabilizing road cuts in the United States, Europe, and Australia.

Cultivated Lands

Erosion control on croplands needs special emphasis as these are the lands with the most potential for alleviating food scarcities in developing countries. The effects of cover and agricultural management have been discussed in chapter 4 under the C and P factors. Although these effects are closely interrelated and difficult to evaluate independently (Wischmeier and Smith 1978), implementation of sound practices is a powerful tool for minimizing accelerated soil erosion.

Use of Cover Crops. At the risk of being repetitious it is emphasized again that maintaining adequate cover is probably the best means of minimizing or preventing soil erosion. For example, at Dehra Dun, north India, Patnaik (1975) found specific losses of 42 Tm/ha under 1250 mm of natural rainfall (June to October) on bare fallow soil with 9 percent slope. Under the same conditions, natural grass cover reduced soil losses to 1 Tm/ha. In addition to protecting against erosion, cover crops smother weeds and may be incorporated into the soil as green manure (Constantinesco 1976). Their importance increases when the primary crop is slow growing or planted at low density. The effectiveness of cover crops depends on such factors as density of foliage; root growth characteristics; water retention, depletion, and penetration; soil fertility; and so on (Sharma et al. 1976). Some examples follow to illustrate the use of cover crops for erosion control in various tropical countries.

In rubber and oil palm plantations of Sumatra and Java, *Calopogonium mucunoides* has been used for over fifty years as protective cover on newly planted plantations (Milsum and Curtler 1925). Other legumes used are *Centrosema pubescens* and *Pueraria phaseoloides*. Cover plants have been classified into two groups. One includes the low-growing type suitable for direct control of splash and sheet wash such as *Calopogonium mucunoides, Centrosema pubescens, Indigofera endecaphylla,* and *Pueraria phaseoloides,* to name a few. The other group is composed of erect-growing types that are more suitable for green manures, including *Tephrosia candida* and *Crotalaria anagyroides* (Bunting and Milsum 1928). *Mucuna cochinchinensis* has great promise according to ongoing experiments in Malaysia.[1] It grows faster and more vigorously than conventional legume covers such as *Calopogonium mucunoides, Calopogonium caeruleum, Centrosema pubescens,* and *Pueraria phaseoloides.* However, Mucuna fades out in 8 to 10 months so that it is necessary simultaneously to plant *Pueraria phaseoloides* or *Calopogonium caeruleum* in addition, to take over when Mucuna withers and dies (RRIM 1977). The free rooting perennial herb, *Alternanthera brasiliana,* which is propagated by cuttings, is highly recommended as a ground cover on the edges of large terraces of oil palm plantings in Malaysia (Duckett and Tan 1974). Newly planted stands of rubber trees are vulnerable to soil loss until the canopy closes after five years of growth. A comparative study of several forms of cover vegetation, including legumes and a grass, was made on an immature stand of rubber trees in Malaysia (see Table 59). The amount of soil deposited on the terraces from the inter-rows, which had various covers, was used as an indication of the efficiency of each cover practice for erosion control. It is noted that *Calopogonium* was twice as efficient in preventing soil loss as *Pueraria,* and over three times as effective as bare soil. In Verma's (1968) assessment of the value of the protective canopy provided by several common Indian legumes, moong *(Phaseolus radiatus)* provided good early cover and protected the soil from the high-intensity July rains. Similarly, it was found in Guaiba RS, Brazil that soybeans *(Glysine max)* gave better protective cover than wheat *(Triticum aestivum)* (Eltz et al. 1977).

Multiple Cropping. Multiple cropping is an agronomic practice that is both highly productive and soil conserving. Whether it takes the form of sequential cropping that limits the bare fallow time between crops, or inter-row cropping that limits the spatial extent of bare soil within a field, the result is the same. At any given time, cover absorbs the forces of raindrop impact and slows down runoff. For example, an erosion-vulnerable period of three to five years exists in tea plantations from the time of felling and clearing the old trees until the newly planted trees develop a complete canopy. During this period mulching or inter-row planting of oats is recommended in East Africa (Othieno 1975). A beneficial form of cover/mixed cropping used in the coffee-growing areas of East Africa is to grow bananas and coffee together. The banana plants provide shade to the coffee and the fallen leaves of the former serve as an anti-erosion mulch (Constantinesco 1976). Studies in Kanpur, India (Sharma et al. 1976) indicated that a pure crop of urd *(Phaseolus mungo)* and a mixture of arhar *(Cajanus cajan)* and groundnut *(Arachis hypogaea)* were most effective for controlling splash erosion among the crops studied, which also included maize, sorghum, guar, and soybeans. Soybeans controlled sheet erosion well in orange groves in Minas Gerais, Brazil; however,

Table 59. Comparison of effect of vegetative covers in reducing erosion in Malaysia over a 20-month period

Cover spp.	Soil deposited on terraces (cm)
Calopogonium	5.64
Pueraria	11.07
Crotolaria	15.69
Tephrosia	14.02
Grasses	12.67
Bare	19.04

Source: RRIM 1977.
Rainfall data were not reported.

1. William Broughton, then of the University of Malaysia, Kuala Lumpur. Personal communication, 6 June 1978.

tree growth and fruit yield decreased because of the competition (Pacheco et al. 1975).

Among the important practices recommended in the Philippines is that citrus orchards should be interplanted with cover crops. For example, in the provinces of Batangas and Camarines Sur, citrus groves are planted to the legumes, *Calopogonium caeruleum,* and *Pueraria javanica* (tropical kudzu). Ipil-ipil and Madre de cacao are also used as cover crops in Batangas. When the plants are about a meter high they are cut back to about 80 cm and the trimmings are allowed to fall to the ground, thus supplying nutrients and reducing soil loss (Hernandez n.d.).

Strip-cropping is a means of "dividing land into alternate strips of close growing, erosion resistant plants such as grass, grass/legume mixtures, small grains, or natural vegetation with strips of wider spaced crops such as maize, sorghums, cotton and root crops" (Constantinesco 1976). Almost invariably the practice is done across the slope, that is, on the contour. An indication of the success of the technique may be obtained from Table 60 in which soil losses are compared between cotton and cotton planted in strips with soybeans and soybeans/stubble. Soil losses were always greater for cotton alone and the effectiveness of strip-cropping in reducing soil loss increased with greater slopes. This form of multiple cropping may be applied in several ways. For example, rotational field strip-cropping is used successfully with alternate arable strips and grassland. Fertility status is favorably maintained as well when the arable crop is rotated with the grass. Buffer strip-cropping is another form in which permanent strips of grass, rarely more than 1.2 to 3 m wide, are left between cultivated areas (Constantinesco 1976). Figure 33 illustrates some of the alternatives of strip-cropping.

Crop rotation, as a form of multiple cropping, is an established method of maintaining soil fertility and reducing erosion. A grass or grass/legume mixture (ground cover) alternated in time between an annual crop such as maize will provide the soil with excellent cover as well as fertility when the residues are plowed under. Apart from the protection provided by the ground cover, the annual crop will provide a denser, more thrifty stand by restoring fertility to the soil. It will thus increase soil coverage, thereby limiting erosion.

Shifting cultivation is the earliest and simplest form of rotation used by humans (see chap. 4). A "short" period of cultivation is followed by a "long" period of fallow. As fallow periods become shortened, it has been suggested that use of specialized crops between annual crops will prevent soil deterioration. "Experiments in Africa using star-

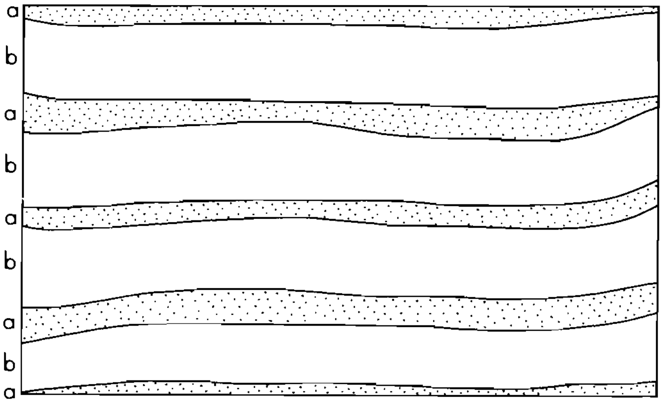


Figure 33. Generalized diagram of strip cropping. ***a*** **= grass or grass/legume;** ***b*** **= maize, sorghum, cotton, or root crops. (Modified from Constantinesco 1976)**

Table 60. Seasonal soil loss from Cecil clay loam (Alabama) planted to cotton and to cotton strip-cropped with soybeans

	Rainfall (cm)	Cropping System	Soil loss (Tm/ha) Slope (%) 5	10	15	20
Early summer	35.43	cotton alone	7.82	15.85	57.37	53.04
		cotton, soybean strips	6.18	8.43	12.72	16.21
Late summer & fall	21.64	cotton alone	2.78	3.16	13.56	16.55
		cotton, soybean-stubble strips	2.35	2.47	3.77	4.41
Entire growing season	57.07	cotton alone	10.59	19.00	70.91	69.59
		cotton, soybean strips	8.53	10.90	16.83	20.63

Source: Modified from Bennett 1939: 349.

grass *(Cynodon plectostachyum),* elephant grass *(Pennisetum purpureum)* and weeping lovegrass *(Eragrostis curvula)* in rotation with maize, tobacco, and forage crops suggest that the residual benefit of the grass ley is best in the first year'' (Constantinesco 1976); by the third year, when the grass is plowed in, there are no benefits. Rotations planned for erosion control should be short, with quick changes from cash to forage crop and back again. For example the best alternative rotations for growing tobacco in Zimbabwe are one year of weeping lovegrass followed by two years of tobacco or two years of grass and four years of tobacco. Both have the same crop-to-grass ratio but soil loss averaged 12 Tm/ha/yr in the first rotation and 14.75 Tm/ha/yr during the longer rotation (Hudson 1971).

High Density Planting. A very effective way to improve the cover is to increase the density of the planted crop. For example, Hudson (1971) has shown that maize grown in Central Africa at 25,000 plants/ha (0.4 m apart in 1 m rows) lost 12.3 Tm/ha of soil in one year. When the plant population was increased to 37,000/ha (0.27 m apart in 1 m rows) annual soil loss was only 0.7 Tm/ha (Table 61). Of course, with the increased plant density, necessary adjustments in management, such as fertilizer additions, are required. There is also a density limit above which competition between plants limits production severely. Overall, implementation of good agronomic practices will reduce soil losses and must be considered as an integral component of the strategy for effective soil conservation (Shaxson 1981). It has been said that if all maize grown in Africa were produced at an average yield of 5 tons/ha rather than about 1 ton/ha as at present, then half the erosion problems of the continent would disappear (Hudson 1971).

Mulching. Mulching is an important erosion control technique, especially on cultivated lands and construction sites. Mulch is a natural or artificial layer of plant residue or other material, such as sand, gravel, or paper, covering the soil surface (SCSA 1976). The mulch material takes many forms—from unused plant remains, wood shavings, and jute netting to bitumen, plastics, and chemical sprays. Its greatest protective value is manifested when the land would otherwise be left bare, that is, after harvesting, before planting, and during early stages of crop growth.

Frequently used natural mulches in the humid tropics are sugarcane bagasse, banana leaves, coconut fronds, and straw from grain crops. Mulches absorb the direct impact of raindrops and thereby minimize soil detachment by raindrop splash. In addition runoff is slowed down and losses are reduced because the infiltration rate of the soil is maintained at its maximum level (Lal 1975). Some workers suggested that mulching enhances the activity of earthworms in soils. Table 62 shows the effect of mulching on earthworm populations in Nigeria. Earthworms improve soil permeability and allow high infiltration rates to be maintained.

The benefits of mulching for reducing soil losses are well established and were discussed in chapter 4.

Table 61. The effect of crop management on soil and water losses from maize in Zimbabwe

	Plot A Medium production level	Plot B High production level
Plant population	25,000 plants/ha	37,000 plants/ha
Rainfall	1130 mm	1130 mm
Fertilizer application	N 20kg/ha; P_2O_5 50kg/ha	N 100kg/ha; P_2O_5 80kg/ha
Crop residues	Removed	Plowed in
Crop yield	5 ton/ha	10 ton/ha
Runoff	250 mm	20 mm
Soil loss	12.3 ton/ha	0.7 ton/ha

Source: Modified from Hudson 1971: 199.

Some evidence that confirms these benefits exists in the tropics. At Apiodoume, Ivory Coast, West Africa, two plots were observed by Roose (1975*b*); one was a natural rainforest, the other a banana planting that was mulched with straw from Guatemala grass *(Tripsacum laxum)* at 20 Tm/ha. Measured soil loss, at 0.1 Tm/ha/yr, was essentially the same under both conditions. Another example of the value of mulching in preventing soil loss is evident from Table 63, where unmulched plots always lost more sediment than their mulched counterparts.

Although mulch material may be transported from one site and applied elsewhere this is an expensive and time-consuming process. Such a procedure may be used in labor-intensive situations, but agriculturally it is generally easier to grow a live source of mulch in which the desired crop is planted in strips opened by tillage or use of herbicides. Experiments with *Stylosanthes gracilis* and maize in Nigeria (Lal 1975) showed that this combination is effective for erosion control, but that the former aggressively competes with the latter for available water. Perennial crops in Uganda, such as bananas and coffee, are generally mulched, and banana mulch is used on coffee plantations in Tanzania (Ahn 1977).

Mulch farming is not equally successful when used under different climatic zones or farming systems (Lal 1981). A problem with mulch farming is that it is difficult to prepare the seedbed for the following crop with mulch on the ground. Herbicide management will allow such a preparation to take place under cultivation with reduced tillage. Disc harrowing will incorporate some of the mulch with the soil, but in many developing countries where animal-drawn machinery is used, the technique is unpopular with farmers, although it should be encouraged (Constantinesco 1976). Other frequently encountered problems are the excessive rates of residue decomposition in certain regions and the tendency to enhance the proliferation of pathogens in others (Hatch 1981).

Construction Sites

Construction sites, including highways and urban developments, are particularly prone to heavy soil losses unless great care is taken. In most countries official soil conservation agencies have been established to help the developer and homeowner as well as the farmer. Direct consultation is usually available to the builder, in addition to written information such as leaflets and bulletins on minimizing soil loss. For example, the following recommendations were made for construction activities in Hawaii, and generally apply elsewhere (SCS 1971).

1. Preparation of a ground plan for the outside is as necessary as a floor plan for the inside.
2. Buildings should be planned to conform to natural topography in order to minimize grading.
3. Disturb only the construction area. Do not clear an extended area unless construction will start immediately on the whole area.
4. Protect trees and shrubs that are to be retained.
5. Stockpile and save topsoil for final grading of the lawn area.
6. Protect the bare soil during construction.
   a. Complete driveways, grading, and sodding as quickly as possible.
   b. Protect bare areas, such as stockpiles, with mulch. Sugarcane bagasse spread 2 inches deep and secured with fiber netting is excellent.

Table 62. Effect of mulching on earthworm casts in maize in Nigeria

Treatment	Worm casts/m^2	Equivalent weight of casts (tons/ha)
Mulched	568	127
Inter-row mulch	264	59
Unmulched	56	13

Source: Modified from Lal 1975.

Table 63. Effect of mulching in Nigeria on sediment density in runoff water under maize

Slope (%)	Sediment density (g/l)	
	Unmulched	Mulched
1	0.28	0.00
5	9.76	0.36
10	7.00	0.45
15	5.75	0.08

Source: Lal 1975.

c. If stockpiles or rough-graded areas are to be exposed for several months, seed with ryegrass as temporary cover and irrigate if necessary for establishment.
7. Control runoff water with temporary diversions and silt traps.
8. Finally, remove all debris and grade to provide adequate drainage. Then prepare the seedbed, fertilize, and establish permanent vegetation. When seeded, erodible areas should be mulched.

Cover plants recommended (SCS 1976) for use on construction sites in Hawaii are Bahia grass, Bermuda grass, Buffelgrass, pangola grass, Kikuyu grass, oats, ryegrass, Lippia, Waipahu fig and Wedelia. Most of these probably thrive throughout the tropics. The mulching materials recommended by the SCS (1976) for Hawaii are sugarcane bagasse, pineapple trash, sawdust, and planar shavings. On steep slopes or under strong wind conditions, these must be anchored with asphalt spray or jute netting. Use of hydroseeding is common on steep slopes of both building sites and road banks. European countries are rapidly accepting soil conditioners to stabilize slopes (De Boodt 1975), but Roose (1975*b*) in the same publication, stated that straw (< 10 Tm/ha) will protect roadbanks effectively against erosion. In Malaysia, Soong and Yeoh (1975) found that latex-oil emulsions sprayed on highly erodible exposed soil surfaces reduced soil losses by 80 to 87 percent during the monsoon season, compared with untreated soil. Latex oil is a by-product of the rubber industry. Incorporation of grass seeds *(Axonopus compressus)* with the emulsion caused a reduction of 93 percent in soil losses in comparison with the untreated soil surface.

Mechanical Control Methods

Above certain limits—particularly those related to topography—the vegetative or biological methods of erosion control discussed earlier may not be effective on their own. Although it is difficult to generalize about the slope limits for vegetative control methods, Sheng (1979) has stated that grass barrier plots on 17° slopes in El Salvador were ineffective (producing a soil loss of 124 Tm/ha) as was the case in Taiwan on 18° slopes. It is important to recognize that the limits that necessitate supplementary mechanical control measures are generally dictated by prevailing slope and land use. The remainder of this chapter will describe the so-called mechanical techniques of control, most of which originated in the West (Moldenhauer and Foster 1981; Meyer 1981; Chisci 1981) and have been tried in some developing countries in the tropics (Hurni 1981; Barber et al. 1981; Bonsu 1981). Most generally these techniques involve soil and land manipulation, either manually or by machinery, and sometimes the use of various fabricated structures.

Conservation Tillage

Minimum Tillage. For many years the conventional tillage operations used in intensive agriculture in developed countries have been plowing, discing, planting, and cultivating. More recently, in response to environmental pressures and oil shortages, the concept of minimum tillage has evolved; this does not define a specific system of tillage, but refers to any system of tillage with fewer operations than the conventional one (Wittmus et al. 1973). The most radical is the no-tillage (no-till) system, in which the only soil manipulation is to open a trench or slot in the sod of the existing vegetation. The trench must be wide enough to receive the seeds or roots of the transplant and to provide seed or root coverage. Weeds are controlled by herbicides, crop rotation, and/or plant competition (Young 1973). The ultimate in row crop production in the United States is continuous no-till corn culture with three tons of residue on the surface. This practice is nearly as effective as permanent grass for water or wind erosion control (Wittmus et al. 1973). Minimum tillage may approximate rather closely the conditions found in several traditional tropical cropping systems such as shifting cultivation and rudimentary sedentary tillage.

Recent data from Brazil compared conventional and no-till cultivation on three successive corn crops on two soils (Benatti et al. 1977). On the Latosol Roxo soil, erosional losses were 20 percent lower from the no-till than the conventional plot; on the podzolized Lins and Marilia plots, no-till controlled 63 percent of soil losses compared to conventional tillage. The corn grain production was similar or smaller in the no-till than the conventional systems (Benatti et al. 1977). In Nigeria, Lal (1976*a*) reported negligible soil losses from no-till culture of soybeans, and attributed this to improved soil water storage and infiltration.

Contour Tillage and Ridging. Performing tillage operations and planting crops on the contour (across slope) rather than up and down slope often results in reduced soil loss. The practice was proven most useful on slopes of 3–7 percent in the United States (Wischmeier and Smith 1965, 1978). An effective variation of this method is contour ridging (listing) in which ridges and furrows are formed by listers (ridgers) and then maize, for example, is planted in the furrows. Another modification is contour strip-cropping, a practice in which strips of sod are alternated with strips of row crops or small grain planted on the contour (Wischmeier and Smith 1965, 1978). This is also more effective than contouring alone. Two cautions should be noted: In the absence of drainage provisions, if rainfall exceeds the retention or acceptance capacity of the soil, breakover of ridges may occur, and subsequent scouring may create greater erosion damage than that incurred from up-and-down-slope tillage and planting practices. Likewise, establishment of grass strips as little as 5 percent off the contour can result in very high soil losses. In the extreme, a fivefold acceleration of soil loss was observed from parallel-to-slope ridges when compared with non-ridged land in Africa (Kowal 1970). In summary, contouring and ridging should be used only on gentle slopes, should provide for drainage of excessive overland flow, and, when applied as the sole conservation measure, the contour rows should be laid out with precision and deliberately maintained to avoid breakover. Correctly done, contour strip-cropping and contour ridging are more effective than contouring alone.

Several other agronomic methods are used on gently sloping land. One is basin listing or tied ridging (Constantinesco 1976), a technique that establishes a large number of small basins in a cultivated field by creating numerous small dams in the furrows with a tying mechanism or shovel. Water ponded within the basins will ultimately percolate into the soil provided the soil is permeable. Contour bunding is another practice similar to tied ridging in that it is intended to be both soil conserving and water conserving. Used mostly in India, bunds are wide channels of level to low gradient, with the ends turned upward (Hudson 1975). However, Krantz et al. (1978) criticized the use of bunds as being ineffective for erosion and runoff control in the semiarid tropics. Considerable water and sediment movement can take place between consecutive bunds resulting in irregular crop performance for various locations in the field. Also the bunds are susceptible to frequent breakover as excess water concentrates at the lower end of the field. This causes more serious erosion than in the absence of bunds.

The mechanical control practices discussed so far are useful only on gentle slopes. However, with increasing population pressures in developing countries (see chap. 2), farms established on slopes of 20°–25° (36–47%) or more are not uncommon. To our knowledge, the extreme is found in Guatemala where the native Indians have been forced to farm lands with slopes as steep as 65° (214%) (Nadel 1976). Under such conditions it is imperative to reduce runoff volume and velocity by decreasing the length of slope and reducing the gradient in portions of the slope.

Terracing

Soil conservation terraces are artificial earth embankments constructed across slope at regular vertical intervals down the slope. They cut sloping land into narrow steps or platforms that effectively reduce the slope length and gradient within the cultivated portion (Constantinesco 1976). Runoff that collects on the terraces may be conserved (e.g. in semiarid regions) or disposed of through drainage into artificial waterways. Following the classification of Sheng (1977*a*), six major types of terraces will be described (Fig. 34).

Bench Terraces. Bench terraces are level or slightly sloping steps or platforms that run across the slope. The steps are supported by steep risers of earth protected by grass, or the risers may be constructed of rock walls. The terraces may be level, outward sloped, or inward sloped, the latter being preferred for the higher rainfall areas of the humid tropics. Level benches provided with enclosing dikes are particularly suited to paddy culture, while outward sloped benches are appropriate to semiarid regions with low rainfall intensity.

Sheng (Sheng and Stennett 1975) believes that bench terracing is particularly suitable for countries having steep slopes, dense populations, food shortages, high unemployment, and high rainfall intensity causing severe erosion. At Dehra Dun, India, Patnaik (1975) illustrated the efficacy of bench terracing over contouring on steeper slopes (25% in this case). Potatoes planted on the contour lost 15 Tm of soil/ha; soil losses were reduced to 1 Tm/ha on 3 m wide bench terraces with a 2.5 percent inward slope. Both sites received 1295 mm of rain. Engineering specifications are covered by Sheng (Sheng and Stennett 1975) and construction of terraces requires design and maintenance; they are not merely randomly placed steps on hillsides. A maximum slope of 30° (58%) is the practical limit for

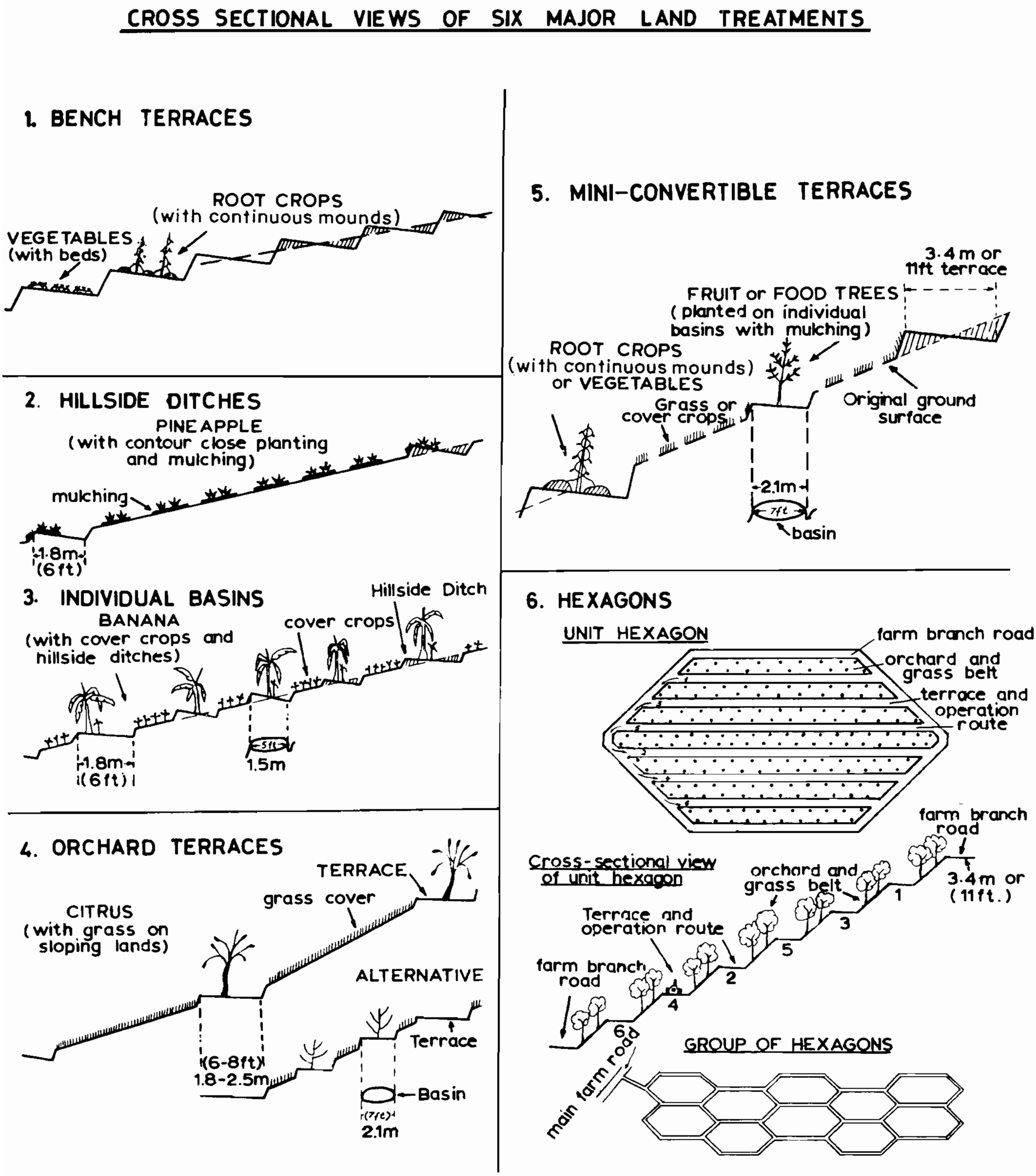


Figure 34. Major types of terraces. (Sheng 1977*a*)

bench terracing for cultivation; in Jamaica it is 25°. Limits are also placed on the length of the benches (100 m in Jamaica for example; Sheng and Stennett 1975); otherwise the velocity of runoff will be too great. Bench widths vary from 2.4 to 5.2 m for handmade benches and 3.4 to 6.4 m for those made with machinery.

Hillside Ditches. Hillside ditches are used to break a long slope into a number of short slopes so that runoff will be safely drained without causing erosion (Sheng and Stennett 1975). The most useful ditch is essentially a narrow reverse sloped bench. Only interspaces between ditches are cropped, so that contouring, mulching, or some other conservation treatment must be applied to prevent soil loss to the ditches. In both Taiwan and Jamaica, pineapples are successfully raised with this cultural system.

Individual Basins. Small round benches of approximately 1.5 m diameter are constructed for individual plants such as bananas or citrus. By themselves these basins are not enough to control erosion and hillside ditches are also installed, with cover crops between the basins and ditches. Individual basins of this sort have been used as well for direct seeding of forest tree species on steep slopes. This is an important conservation technique where land is dissected, where soil depth varies from deep to shallow, or where rocks and stones are present in large quantity (Sheng and Stennett 1975).

Orchard Terraces. These are essentially bench terraces constructed for fruit or food trees on steep slopes (25° to 30°). An inclination distance of 6.1 m is recommended for most orchard terraces and the space between the benches should be kept in permanent grass (Sheng and Stennett 1975).

Miniconvertible Terraces. Miniconvertible terraces have 3.4 m wide bench terraces interspersed with 1.5 to 2.1 m basins. Fruit or food trees are grown in the basins and vegetables or yams on the terraces, with grass or cover crops in between. This conservation practice provides greater flexibility than the other terrace procedures. If more intensive agriculture is desired, the slope can be converted solely to bench terraces. If less intensive agriculture is desired, then all the terraces can be planted to fruit or food trees (Sheng and Stennett 1975).

Hexagons. The "hexagon" method, designed for large or medium sized commercial orchards on sloping land, originated in Japan. As noted in Figure 33 the hexagon is formed by a farm branch road that encloses the orchard. Operation routes of four-wheeled tractors meet the farm branch road at an obtuse angle.

In order to design terraces in the field, many farmers and conservationists in the United States and elsewhere use a terrace-spacing formula (SCS 1975*a*) unless local conditions dictate other dimensions (Fig. 35). The formula for vertical spacing is:

$$VI = XS + Y \tag{13}$$

where VI = vertical interval in feet; X = a variable from 0.4 to 0.8 that is dependent on rainfall intensity. (The Gulf States in the United States are assigned a value of 0.4, while drier states of the north central region, Northwest, and West have a value of 0.8); S = land slope in ft/100 ft; Y = a variable from 1.0 to 4.0. (Soils with below average water intake rates and cropping systems providing little cover have a value of 1.0, while 4.0 is assigned where tillage systems leave considerable cover).

For maximum horizontal interval the formula is:

$$HI = (XS + Y)\left(\frac{100}{S}\right) \tag{14}$$

where HI = horizontal interval in feet; and the remaining terms are defined as before. It is important to note that both formulas 13 and 14 require site-specific values that are often not verified before use, with subsequent over- or under-designing of terraces.

The universal soil loss equation lends itself to

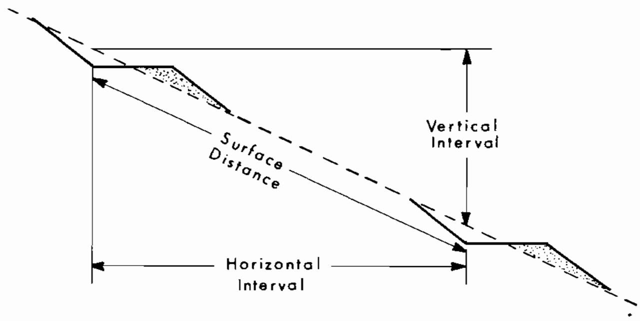


Figure 35. Horizontal and vertical interval measurements for spacing terraces. (Beasley 1972)

evaluating the horizontal interval of a terrace if the L and S factors are available.

$$HI = \left[\frac{100\,SL}{0.76 + 0.53s + 0.076s^2}\right]^2 \qquad (15)$$

where s = land slope in percent, and SL = E/KRCP, where E = allowable soil loss in tons/acre/yr, and K, R, C, and P are defined as in chapter 4.

However, this formula is not widely used outside the United States because quantitative values for the factors of the equation are not generally available. A report of a recent application in east Africa was provided by Hurni (1981).

Waterways

Although the various contouring and terracing techniques already described are used to reduce the velocity of flow and thus the scouring effect of runoff, excess water must be disposed of in definite channels, or artificially constructed waterways (Fig. 36). Specifications and design criteria are provided in the Engineering Field Manual (SCS 1975*a*), Hudson (1975), Beasley (1972), and other agricultural engineering books. Waterways take many different forms, some of which are explained below.

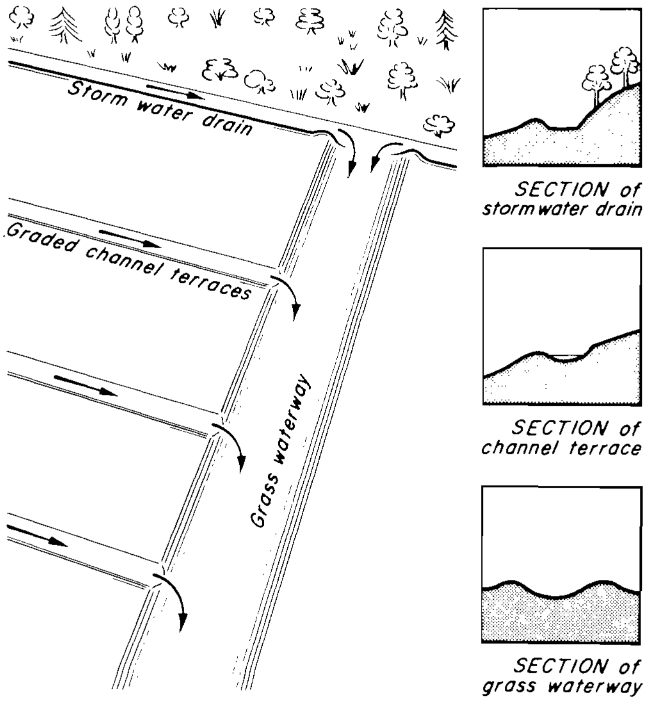


Figure 36. Major kinds of waterways. (Hudson 1971)

Diversions. A diversion is an individually designed graded channel with supporting ridge on the lower side, and is constructed across slope (SCS 1975*a*). Variously called storm water drains, diversion ditches, or diversion terraces (Hudson 1971), they are the first line of defense for protection of the cultivated area where there is danger from extraneous runoff from pastures or timberland above the cultivated land (Constantinesco 1976).

The major uses for diversions are to reroute water around gully heads, to protect lower terraces by diverting water from the upper terraces, to break up water concentrations on long gentle slopes, to reduce the length of slopes in conjunction with other conservation measures, to collect water for water harvesting systems, and so on. Cross sections of diversions may be either parabolic, trapezoidal, or V-shaped. The success or failure of a properly designed or constructed diversion is dependent on the outlet and on proper maintenance. Repair of damaged grassy areas in the sod and elimination of weeds are essential.

Channel Terraces. These channels are located across the slope so as to further interrupt the flow of water across the cropland. According to Hudson (1971) they are termed ridges or bunds in Commonwealth countries. They may be slightly graded or, in semiarid areas, built perfectly on the contour to absorb available water. Generally their shape is trapezoidal or V-shaped in cross-section. For most soils, water flow velocity in the channel should not exceed 0.61 m/sec if the channel is cultivated; 1.1 m/sec if not cultivated (Beasley 1972). Broad-based terraces (broad-based contour ridges) up to 15 m wide, in which row crops can be grown, are found in Zimbabwe and South Africa. The narrow-based contour ridges with steep-sided banks are up to 4 m wide and cannot be crossed by tractors; they are often found on tobacco fields in Africa (Hudson 1971).

Grassed Waterways. Grassed waterways are constructed waterways shaped to desired dimensions and vegetated for safe disposal of runoff from a field, diversion, terrace, or other structure (SCS 1975*a*). When used as an outlet for terraces they are often called "terrace outlets" (Beasley 1972).

Grassed waterways should be constructed in advance of other channels that discharge into them. Three shapes (parabolic, trapezoidal, V-shaped) are used but the parabolic cross-section is most satisfactory. The location of the grassed waterway should conform to the flow pattern of the area and ideally may be located in a naturally vegetated draw. Oftentimes gullies may be shaped into grassed waterways with bulldozer work followed by the planting of grass. Generally the flow velocity in the channel will vary from 0.91 to 2.13 m/sec depending on the soil type and vegetation present. In India it has been recommended (Shankarnarayan and Magoon 1974) that *Cynodon plectostachyus, Urochloa mosambicensis, Dichanthium annulatum,* and *Cynodon dactylon* may be used in waterways. Further to the north in Nepal it was found that thin Napier grass *(Pennisetum polystachyon)* had a greater basal area coverage, had a higher yield, and retained more silt than two other grasses tested for waterway stabilization (Sachdeve et al. 1976).

The selection of grasses for planting in waterways must be made with view of their adaptability to prevailing soils and the region's environmental conditions. Maintenance requires that damage to the sod be repaired quickly and a dense grass sward must be maintained by occasional fertilization if necessary. The waterway definitely should not be used as a footpath for animals or humans and care must be taken to prevent damage to the sod when moving machinery across it (Constantinesco 1976).

Structures

The installation of mechanical structures for erosion control should be considered a last resort. They are difficult and often expensive to construct and demand expertise in design. As pointed out by Hudson (1975) "Everything is against their being successful. They will be built in adverse conditions, in poor unstable soils, in remote inaccessible areas where maintenance will be poor, and then they will be expected to withstand the onslaught of torrential floods and to last forever." However, where vegetative measures alone or in combination with the land-shaping methods already described will not handle the water concentrations involved, structures may be used if economical. A structure is defined as a designed device, constructed or manufactured, that is used in soil and water conservation to retain, regulate, or control water flow (SCS 1975*a*). They are used specifically for grade and gully control, water storage, water retention (flood prevention), sediment storage, surface-water inlets, water-level control, irrigation, drainage, and shoreline and streambank protection.

The Soil Conservation Service (1975*a*) states that many structures are composed of the following components:

- an earth embankment that directs water through the spillway;
- a spillway inlet that is a box, a weir (dam) in a wall, or a culvert;
- a spillway conduit that is an enclosed box, pipe, or open channel;
- and a spillway outlet that is an apron with or without an energy dissipator or a cantilevered outlet.

Earth Embankments. These are used for ponds, irrigation reservoirs, and grade stabilization structures. As the basis for a silt-trap dam, such embankments have widespread use to reduce the sediment load of downstream water supplies. For example, urban development often requires an embankment during construction, for collecting sediment from the site.

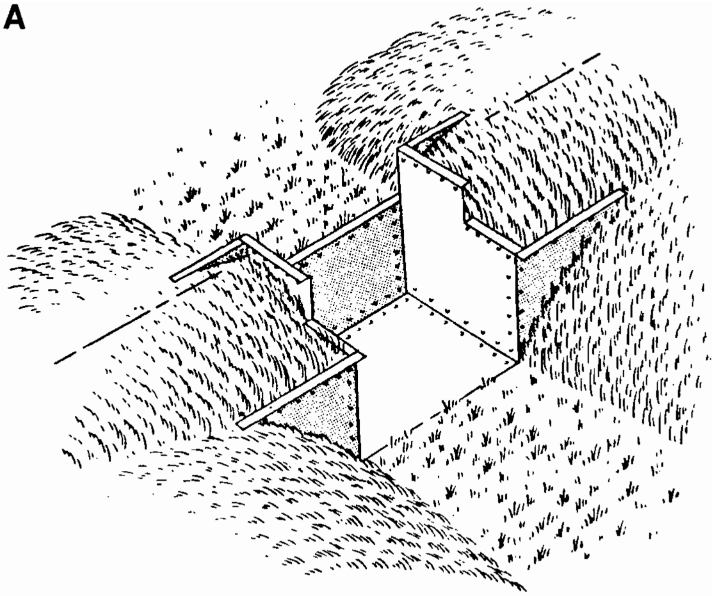
Obviously preliminary survey work is needed to build a functional embankment. The nature of the soil as well as certain geological data must be gathered if an impounding structure is desired. (For example, soils composed largely of shrink-swell clays might be unsuitable.) The presence of pockets of permeable materials, an extreme case being lava tubes in Hawaii, is necessary preconstruction information.

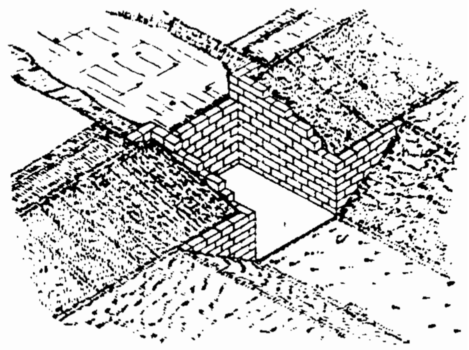
Spillway inlets, conduits, and outlets. Water impounded by an embankment enters the spillway through a box, a weir in a wall, or a culvert-type entrance. In certain structures a conduit (pipe or rectangular channel) carries water through the structure. At the outlet, safe disposal of water is necessary and is accomplished by a stilling basin (the apron of the structure) or strategically placed blocks which serve as energy dissipators.

Figure 37 illustrates several forms of concrete or metal structures that may be used; however a great number of designs have been employed. Obviously none of the foregoing structures should be installed without consulting a knowledgeable engineer. Figure 38 gives a general rule-of-thumb chart to determine the required spillway type.

Various natural or synthetic materials are used to construct check dams that slow the course of water in a gully. A rock-fill dam (Fig. 39) anchored by wire netting is one possibility. Another is the use of wire netting secured by posts. Brush or straw is

A





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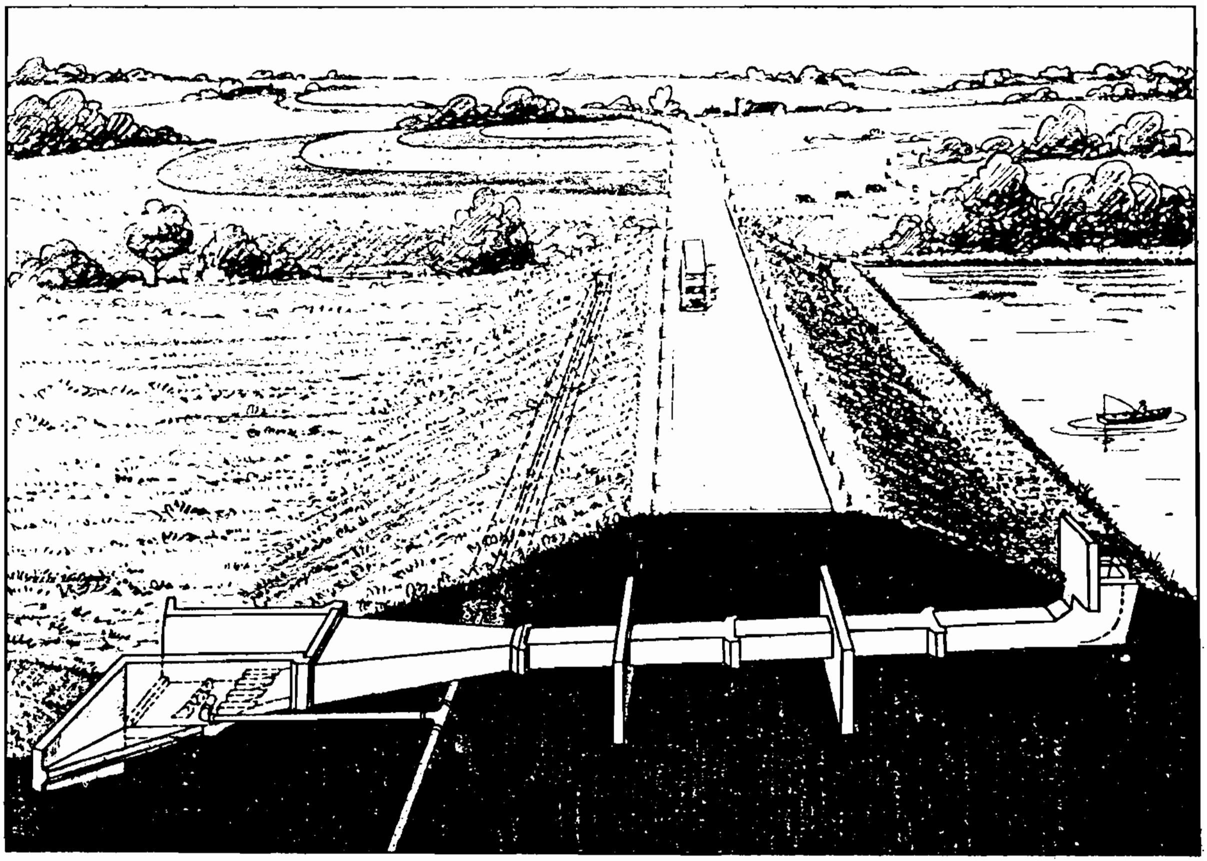
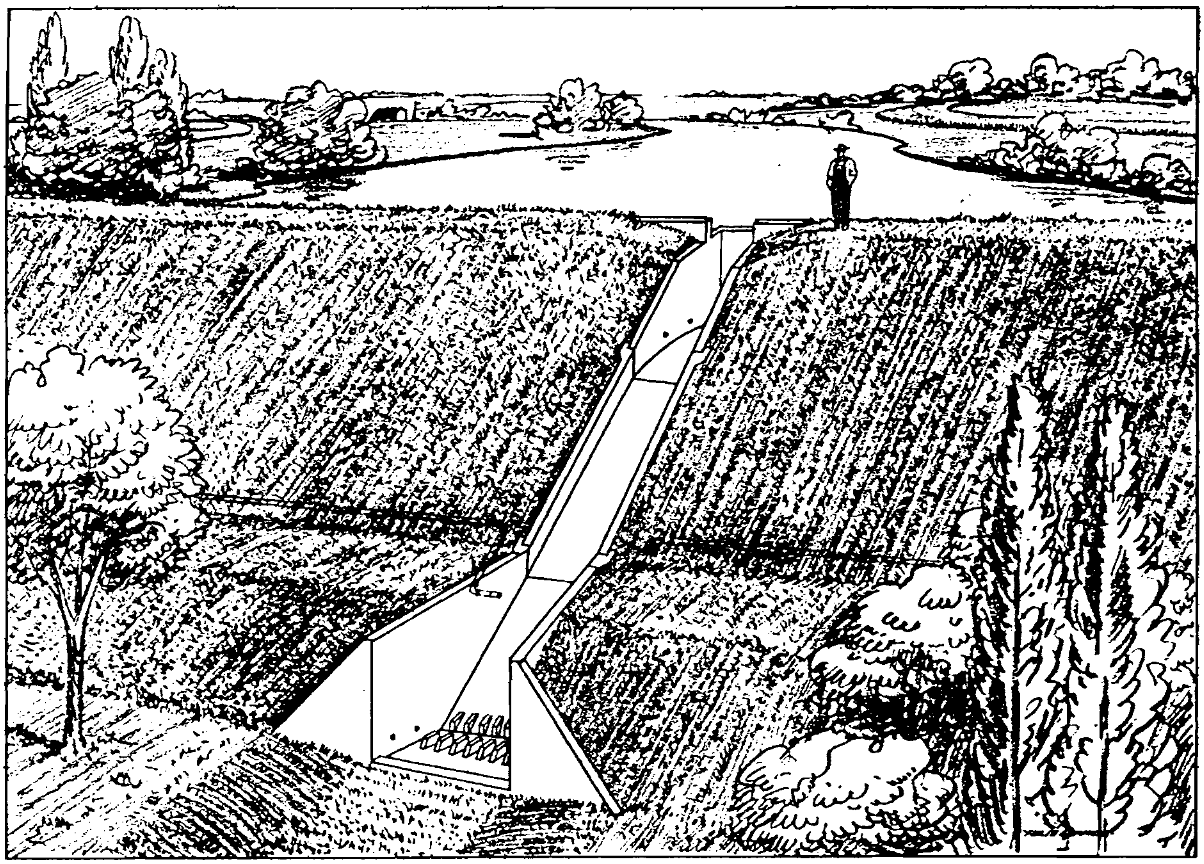


Figure 37. Various kinds of spillways: *A*. Two drop spillways; *B*. A monolithic drop inlet spillway; *C*. A chute spillway. (SCS 1975*a*)

C



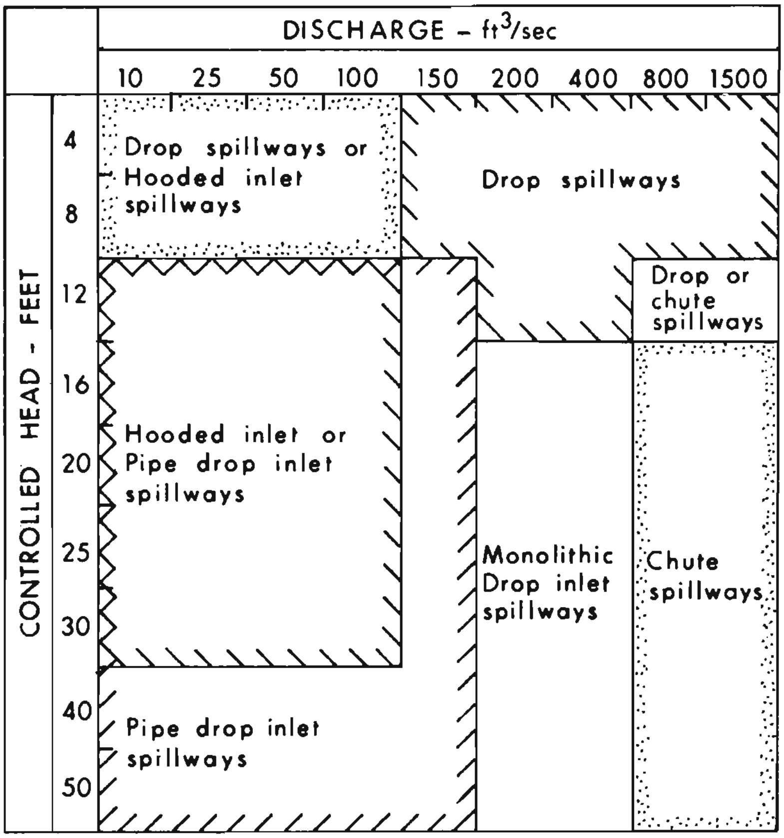
placed on the upstream side of the netting, which slows runoff and builds up sediment upstream of the dam. Brushwood dams (Fig. 40*a*) in which branches are tightly packed together horizontally and secured across the gully by vertical stakes or by tying with wire, are also utilized. A more substantial structure may be constructed with two rows of vertical posts driven into the channel floor and logs packed in between (Fig. 40*b*). If there is considerable flow the dam should have a rectangular notch, which must be wide enough to pass the full flood of water, without restriction, otherwise scouring of the banks will take place. Finally, used or discarded bricks may be used to build a weir. Since such a structure lacks "weep holes," it lacks tensile strength and should be buttressed. More complete discussions of these temporary structures may be found in Hudson (1971) and Weidelt (1975).

Gully Control and Stabilizing Slopes

Hudson (1971) said "In gully control a bag of fertilizer is more effective than a bag of cement." However, it is not always possible to check downcutting and head cutting, the main subprocesses of gully formation, by vegetative measures alone. Tentatively, we accept the classification of Sheng and Stennett (1975) that small gullies are less than 0.9 m deep, medium gullies are 0.9 to 4.6 m deep, and large gullies are over 4.6 m deep. The simple procedure of fencing the gully from cattle, followed by revegetation, may be effective on small and perhaps medium gullies (Constantinesco 1976). Normally, more effort is required for larger gullies.

Generally a diversion (storm-water drain) around the head of the gully is a first step to control runoff (Bennett 1939; Constantinesco 1976). The diversion normally is located above the gully head at a distance of 3 to 4 times the depth of the gully. A safe grade in the diversion is 0.45 to 0.90 m per 100 m (USDA 1973). A general rule of thumb in India is that a gully with a waterway slope up to 19 percent and a small drainage area can be controlled by leveling the slopes and vegetating the gully (Singh 1974).

Although the final objective is revegetation of any gully, mehanical structures may be mandatory for stabilizing head cuts of large gullies and ravines (Heede 1977). In the Philippines these may be brush cover, riprap interplanted with cuttings, pole structures, solid structures of gabions, or occasionally grass sods (Weidelt 1975). Although temporary



Note: Chart shows most economical structure as related to discharge and controlled head providing site conditions are adequate.

Figure 38. Guide to structure selection. (SCS 1975*a*)

Figure 39. A rock-fill check dam. (Heede 1977)

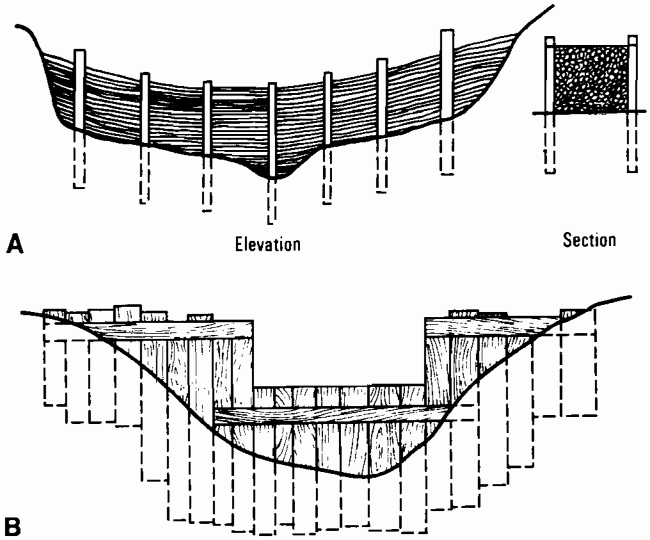


Figure 40. Temporary dam structures: ***A.*** **Brushwood dam;** ***B.*** **Timber and log dam. (Hudson 1975)**

structures are not recommended in the United States (USDA 1973), in the labor intensive societies of many developing countries such structures seem quite justified. Most favored plants for gully control are those of great density, low height, with sufficiently strong vegetative portions to remain erect under intense rainfall impact or overland flow, and with deep dense root systems (Heede 1977). Tall grasses are not generally recommended for gully stabilization as they lie flat under flow impact and may substantially increase flow velocities.

It has been concluded that afforestation alone will not reclaim gullies in western and central India. The problem must be solved on the individual watersheds where peripheral bunds and drop structures at gully heads can arrest gully progress. In the eastern red soil region of India earthen check dams are being used. Paddy benches are developed below the storage dams (Das 1977). Only porous check dams (those with "weep holes") are recommended for wild lands and elsewhere in the United States, as they require less anchoring than the nonporous types. Oftentimes loose-rock check dams (Fig. 39) can be constructed from available rock in the area, using rock alone or with wire mesh, gabions, fencing, and so on (Heede 1977).

Use of flexible stone-filled bolsters has been recommended for trapping silt and reclaiming gullies in Zimbabwe (Stocking 1976). Intensive methods of correcting existing tunnels in Australia involve mechanical and vegetative methods. Initially, contour plowing or ripping is employed, with the threefold purpose of breaking up crusts, aiding water infiltration, and preventing surface water accumulations. True control is then accomplished by revegetating the problem site and proper management thereafter (Stocking 1976).

Grassed waterways may be constructed from existing gullies if the necessary machinery is available. Small and medium-sized gullies may be reshaped with a bulldozer. The channel cross-section should be broad and flat and, after the proper form is achieved, should be seeded with native grasses. Usually the soil in the bed of a reworked gully is poor so that oftentimes sacks (jute, paper, etc.) of good soil are laid in shallow trenches in the floor of the channel. Then the bags are slit and the grass seedlings are planted through the slit. This reduces chances for washing away the soil and seedlings before the grass is established (Hudson 1975). The depth of flow should be 0.15 to 0.45 m to keep the flow velocity between 0.91 and 1.82 m/second. The gradient should not exceed 10 percent (10 m drop/100 m length). Ponds may be located at the ends of the grassed waterways that serve as water-storage areas for livestock, fish farming, or recreation (USDA 1973).

As one example in the tropics, the general principles as stated above have been used to renovate the spectacular *lavakas* in various places on Madagascar. Diversion ditches were provided above the *lavaka* head and the slopes of the walls were reduced to prevent collapse. This was followed by installing log fascines, stone gabions, or holding plant dikes in position with wire netting; revegetating with grasses, such as elephant grass, bushes *(Mimosa)* or trees (*Eucalyptus* spp.); and raising the base level by means of dikes across the outlet (Le Bourdiec 1972).

Control in Lumbering and Land Clearing

Logging operations may cause major erosional problems, especially in the humid tropics where there is accelerated lumbering activity and the rainfall is particularly aggressive. Tree felling itself causes only minor erosional disturbance. Tractor skid trails (snig tracks) and logging roads are most vulnerable to erosion. Studies in northern Queensland indicate that in group selection tractor logging in a rainforest, 18–21 percent of the area is covered with skid trails, of which 70 percent are bare soil (Gilmour 1977). To keep soil loss to a minimum Gilmour proposed the following guidelines:

1. Keep all roads, skid trails, and log ramps as far from streams as possible.

2. Use a logging arch in tractor skidding rather than dragging the logs.
3. Keep the grades for roads and trails as low as possible.
4. Ensure adequate drainage of roads and trails.
5. Practice uphill logging wherever possible.
6. Upon completion of logging, before the rainy season, inspect potential problem areas on roads, and seed or hydromulch where necessary.

Valuable suggestions made by Megahan (1977) for forest road construction in the United States are also applicable to the tropics. Such obvious but frequently ignored suggestions as keeping logging roads as narrow as possible, locating roads away from high erosion hazard sites, and taking advantage of ridge tops, natural benches, and lower gradients for locating roads exemplify the recommendations Megahan made.

A number of suggestions made for land clearing in Surinam (Van der Weert 1974) should apply quite generally throughout the tropics. For example there is generally an inverse logarithmic relationship between the force necessary for compaction and soil water content. Since compaction reduces infiltration of water, all clearing and windrowing should be done during the dry season, and burning should precede windrowing. To keep the number of passages of vehicles as low as possible, distances between windrows should be twice the future plant interrow distance rather than the 40 to 50 meter spacing normally used. Van der Weert suggested that a bulldozer with a K. C. Stinger blade for cutting down trees should be used rather than a bulldozer alone, as the latter causes considerable soil disturbance when uprooting the trees. Finally, stump clearing should be carried out only when stumps greatly impede access to the area.

Row planting of teak in Trinidad (Bell 1973) has caused serious soil losses. Control measures recommended are group planting of teak with shrub growth established between groups; use of unplanted strips by gardeners for one year followed by establishment of shrub growth; and control of burning. Bell even went so far as to suggest elimination of teak altogether as a wood crop in Trinidad if all else fails.

Erosion control on tea estates in Sri Lanka (Lester-Smith 1938) was advocated as a combination of mechanical and vegetative procedures. Hedges of sword plant *(Sansevieria guineensis)* and Ceylon bowstring hemp *(S. Zeylanica)* were recommended for planting on contour as sediment traps. Carpet grass *(Axonopus compressus),* Australian daisy *(Erigeron mucronatum)* and *Indigofera endecaphylla* were advocated for bank stabilization.

Another problem of irregular occurrence in association with logging or clearing is landslides or mass wasting. This is the dominant form of soil loss on steep-sloped watersheds where shallow slides (debris avalanches) are most likely to be initiated by logging or destruction of forest cover. Roads cause slides more frequently than the actual timber harvest although clearcutting reduces slope strength more than any other logging system. Clearcutting is not recommended in steep terrain (Hattinger 1976; Rice 1977). Similarly the effect of fires on slopes in the long term is to increase the risk of slides (Rice 1977).

Torrent flow is another feature of forests that can cause severe problems, especially to forest roads. Roads built parallel to the channel of a torrent, or a road cutting across such a channel, may be severely damaged. In the first instance bank erosion is the main threat to the road; in the second, the culvert, bridge, or paved ford may be damaged, especially if debris blockage occurs (Hattinger 1976). Protection of channel banks is recommended by riprap (rocks); sills and check dams for channel-bed and bank protection; groynes to divert flowing water; and line ditches, check dams, and the like for flood discharge. To protect bridges, culverts, or fords against bed erosion and against blocking, sills and check dams are used (Hattinger 1976).

For stabilizing slopes and road cuts in developing countries, retaining walls of riprap (rocks) are commonly used. Interplanting of the riprap with vegetation may be employed as well (Weidelt 1975). Where stronger structures are needed, gabions are used at the bottom of a slope; these are prefabricated, heavy, galvanized wire baskets filled with rocks. Weidelt (1975) stresses that the first line of gabions should always be inclined toward the slope. An ingenious, and at the same time economical, use can be made of worn-out automobile tires to construct retaining walls or to place them flat on the slopes (Fig. 41). Where possible, vegetation is interplanted in the inner circle of soil defined by the tire (Weidelt 1975).

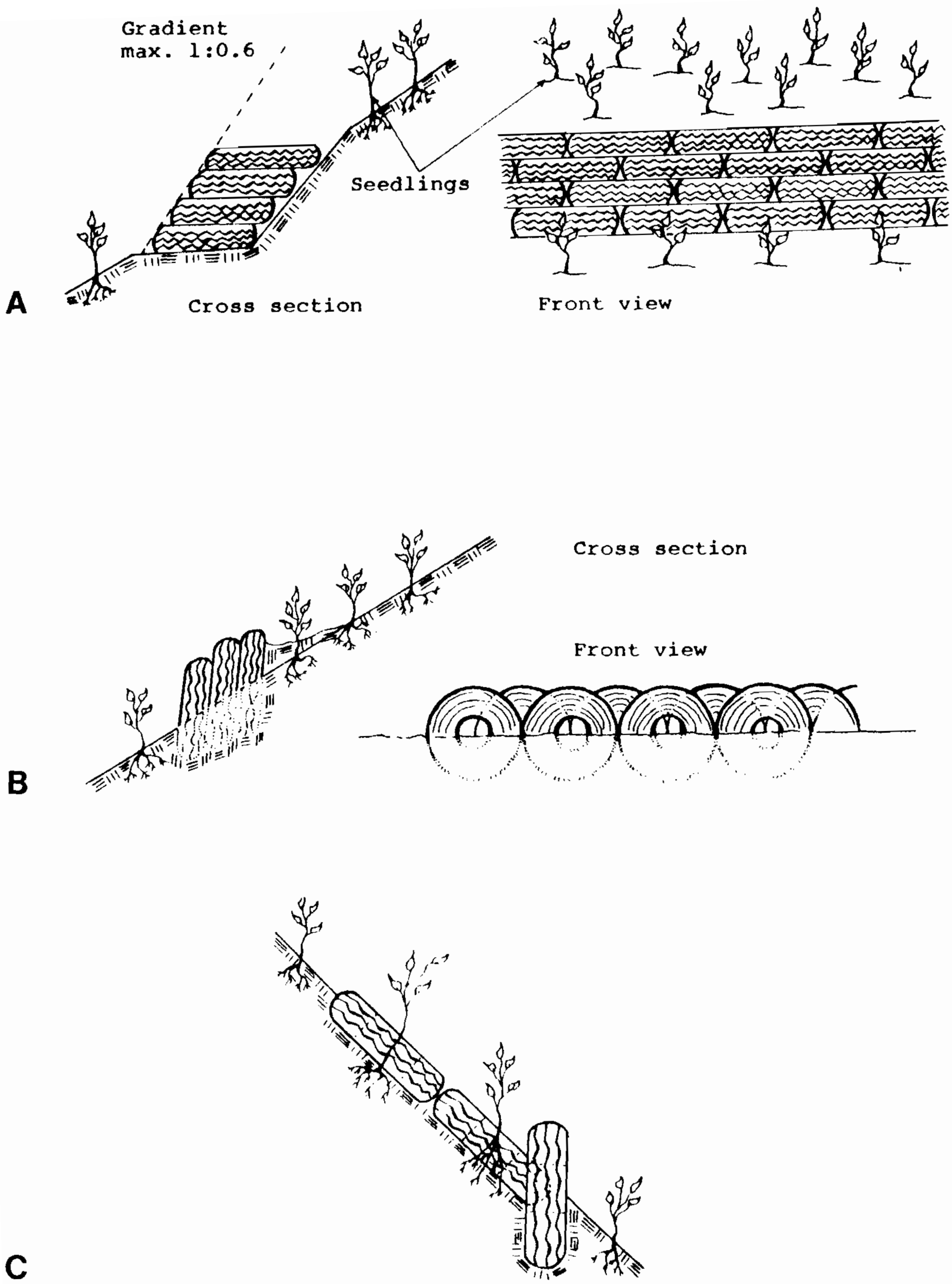


Figure 41. Use of worn tires for stabilizing slopes: *A*. Retaining wall; *B*. Low barrier; *C*. Cover. (Weidelt 1975)

CHAPTER 6
PRIORITY NEEDS FOR PROBLEM SOLVING

In the previous chapters we have pointed out the serious magnitude of rainfall erosion in the tropics, with examples of its overwhelmingly detrimental impact, primary causes, and of technology available for its control. In each of these areas many gaps have been identified that must be filled if soil losses and numerous associated adverse effects are to be prevented or reduced to tolerable rates. To solve the problem, the major needs that emerge are to provide information in sufficient depth and clarity to stimulate the concern of policymakers; to provide a framework for the collaborative collection of vital quantitative data on all aspects of erosion; and to provide the means for transferring available technology to different tropical regions. There is great need to extend effective conservation advisory services to the farm level, and to provide relevant training to conservation research and extension staff in developing tropical countries.

INFORMATION DISSEMINATION

This state-of-the-art report is an attempt to focus on all aspects of rainfall erosion in the tropics. It is the newest, but undoubtedly not the last, in a series of documents, conference proceedings, and other national and international efforts that treat the alarming proportions of the global erosion problem (see chaps 1 and 2). Initiative should be taken by leading international agencies and organizations to insure systematic and timely delivery of these documents, or selections and syntheses from them, to assist researchers, directors, and planning agencies to provide more effective support to policymakers in developing tropical countries. Effective means of delivering this information (such as regular workshops, seminars, written releases, and so on) should be identified. Information should be disseminated in a thorough and regular manner. A concentrated effort should be made to help policymakers implement effective conservation and land-use policies. One means of doing this would be to form a collaborative research and information network—or networks—that would assist member countries to characterize relevant aspects of the problem, assess available base-line data, identify research priorities, and exchange transferable technology. A proposal to form a "Collaborative Network on Soil Erosion and Conservation in the Tropics" (CONSECT) is advanced in the next section.

It is imperative that concern be stimulated, and serious efforts initiated, not only in those countries where erosion and associated problems have already progressed to an alarming extent, but also in others where the problem can (fortunately) still be prevented from causing extensive damage (chap. 2). Human populations in the tropics are expanding at alarming rates and continued indiscriminate exploitation of land can easily produce further irreversible damage to soil, water, and forest resources.

RESEARCH NEEDS

Quantitative Assessment of Erosion Extent, Tolerance Limits, and Causative Parameters within Collaborating Countries

Understanding the existent erosion trends in a given country or region is important not only for identifying critical problem areas but also for revealing qualitative interrelationships among soil losses, adverse effects on productivity, and the relative importance of prevailing causes and land-use patterns. Proposed components of a research program for quantitative assessment of these interrelationships are listed below. More detailed discussions and relevant citations from the literature are included in chapters 2 and 4.

Survey of Existing Soil Erosion

Small-scale surveys, perhaps using remote-sensing techniques, will provide initial information on the distribution of critical erosion areas. Ultimately, however, specific measurements of soil losses, with runoff from specific selected sites, will be needed to determine whether erosion rates exceed "tolerable" limits for these areas. Such monitoring can be effectively integrated with determining causes.

Tolerance Limits and Rehabilitation Requirements

Judgment of the severity of erosional losses from soils must take into consideration original soil properties and the various detrimental impacts of erosion (Young 1980; Mannering 1981; McCormack and Young 1981; chaps 1 and 3). Of particular importance to farmers in developing countries are quantitative changes in soil productivity under major crops as a result of eroding surface soil layers that are richest in nutrients and physically most favorable for root proliferation. Such data are also needed to determine the rehabilitation requirements of eroded lands in order to restore their capacity to support alternative food crops or other desired vegetation.

Rainfall Erosivity

The aggressivity of rainfall, or its inherent ability to induce soil loss, has not been defined for the different climatic regimes within the tropics. Indeed, it may be safely stated that the data necessary to quantify the role of this primary causative parameter are scarce. The individual or combined roles of kinetic energy and intensity of rainfall need to be verified. Monitoring rainfall for these parameters with statistical reliability requires long periods (20 years is often stated as a minimum) and a number of locations, determined by rainfall variability. To avoid the large expenses and delays associated with such full monitoring, simpler indices for quantifying rainfall erosivity need to be tested or developed for wider application in the tropics. Components of erosivity, namely the direct impact of rainfall and the detaching power of overland flow (runoff) need to be separated and quantified. Annual erosivity maps and seasonal distributions of erosive rainfall should be constructed for representative locations within each country.

Soil Erodibility

The inherent susceptibilities of different tropical soils cannot be fully assessed from available data; instead, they should be determined experimentally for representative families or other levels of soil taxonomy, as may be required for reliable categorization and mapping. For this purpose, surface and subsurface horizons need to be distinguished to allow for alternative land uses that may necessitate different magnitudes of soil exposure. Data should be collected simultaneously under simulated and natural rainfall, the first to generate rapid estimates and the second to refine such estimates if needed. The dependence of soil erodibility on structural, hydrologic, and mineralogical properties should be quantitatively determined to allow available experimental values to be extended to soils of unknown erodibility and, equally important, to estimate changes in erodibility that occur with time and alternative uses.

Topographic factors

The quantitative effects of slope length and gradient on runoff and erosional losses are quite obscure for tropical soils. Yet these parameters are of primary importance not only for accurate assessment of erosion hazard, but also for deciding erosion control requirements and methods. In particular, data are needed for slopes of less than 3 percent or more than 18 percent gradient (very common in hilly tropical regions under intensive cultivation) and more than 120 m length. Even in the United States, tabulated data outside these ranges represent extrapolations from experimental data.

Crop Cover and Residue Management

The quality of crop canopy and its protective effects against rainfall erosion during various stages of growth and particularly at various times of the year (in locations where precipitation is seasonal) need to be assessed for the common crops and the different cultivars grown in the tropics. The timing of different cultivation operations, particularly harvesting of underground portions (e.g. in yams) is critical for reducing or increasing erosion hazard. The effects of multiple cropping (with time and space) and of stubble management should be quantified, in both the short and the long term. Evaluations of growth requirements and of the effectiveness of specialty cover crops under different climatic and management regimes are needed. Of particular importance is the direct utility (aside from protecting the soil surface) of such crops to the farmer, a factor that may add to incentives for soil conservation. For instance, fast-growing woody plants may have a secondary application as fuel, whereas more effective but nonpalatable herbaceous ground covers will not have a secondary appeal as animal food.

Land Management and Supporting Practices

The benefits of tillage and the merits of alternative land-shaping and tillage operations remain unresolved for tropical conditions. Whatever supporting practices have been used to manipulate overland flow have usually been designed indiscriminately according to formulae developed outside the tropics. Quantitative data are needed to relate the effects of alternative tillage and land-shaping practices to erosional losses from different soils under different rainfall patterns.

Meeting these research needs will provide an invaluable tool for accurate prediction of erosion hazards and control alternatives. However, it is apparent that meeting these needs for the multitude of climatic patterns, soils, land-use patterns, and socioeconomic conditions in the tropics would require massive efforts. As indicated above, the needed research could be conducted jointly by a network of collaborating institutions—in the United States and developing countries of the tropics—in collaboration with a coordinating body. Such a network, tentatively named CONSECT, could encourage the compilation of all existing relevant data; formulate standardized methodology for collecting needed new data; facilitate data processing and exchange among members; minimize duplication of research; and contribute greatly to meeting the requirements on training and advisory services discussed below.

As a starting point in developing the proposed network, an assessment must be undertaken by interested member institutions of alternative research methods currently available for quantitative measurement of soil erosion causes and control effectiveness. This proposal is detailed in the next section.

Alternative Research Methodologies

Methods for soil erosion research used most frequently in the United States and developed countries in general, tend to be suitable only for locations where personnel with high levels of training are standard or made available (such as certain international research institutes). Where such personnel are unavailable, these methods are too complex and require too high a level of financial investment to be directly usable by interested workers in less developed countries. This is a significant barrier to full appreciation by those workers of research results obtained elsewhere (whether or not applicable to their own needs) and to their engaging in effective and active research to collect their own data. A thorough survey of published literature and other available information on research methodology should be made and assessed by members of the proposed CONSECT in joint regional and global workshops, with cooperators representing appropriate institutions. Recommended (unifying) standardized procedures for erosion research in developing tropical countries could be selected and published. Concurrent evaluations of these methods would preferably be made at selected institutions—to establish correlations between data collected by new and long-standing methods, and also to insure an institution's ability to act as a clearinghouse for collected data if needed. Concurrent evaluations would also be necessary to test the transferability of available U.S. technology, as discussed below.

Testing the Potential for Transfer of U.S. Technology

The current U.S. technology for prediction and control of rainfall erosion is largely based on the use of the universal soil loss equation (USLE). As discussed in chapter 4, the equation is universal only in that it identifies all the parameters that contribute collectively to erosional processes. In this respect, the experience of the United States and elsewhere should, in principle, be transferable. However, empirically derived quantitative values for individual parameters in the USLE as they now exist, are restricted in validity to the mainland United States and can be extrapolated for use in the tropics only after experimental confirmation or modification. Such confirmation or modification should receive a high research priority since the benefits from building upon American experiences would be immense, particularly for early diagnosis of problem areas and prescription of appropriate control measures.

Furthermore, while the major requirements for the transfer of technology pertain to the formulation of the quantitative causative parameters described above and in chapter 4, the application of required conservation practices depends very much on the state of awareness of the farmer and other socioeconomic, cultural, and political conditions in a given country (Dudal 1981; Heusch 1981; Hudson 1981; Stocking 1981; Wiggins 1981). Again, the proposed network (CONSECT), with U.S. institutions as collaborators, can play a vital role, as consultations and exchange of information on local experiences with implementation and advisory services would be of mutual benefit. Ultimately, however, it will be up to the implementing (watchdog) agency within each country to package and disseminate transferable technology as appropriate for local consumption.

EXTENSION, ADVISORY, AND INFORMATION DELIVERY SERVICES

Implementing the technology designed for conservation-effective land use under local conditions will be possible only if locally formulated or modified technological packages are delivered to farmers in a manner compatible with their own conditions and including sufficient incentives to insure cooperation (Shaxson 1981*b*). In many countries, the mechanism is usually a soil conservation service (or authority or commission) controlled by central or regional governments. In the United States, client participation is facilitated by a network of Soil and Water Conservation Districts each of which represents a number of local farmers within a limited area. Districts capitalize on available incentive programs and thus work closely with officers of the Soil Conservation Service, USDA. The utility of a similar system, or of alternative models, for disseminating information and providing conservation advisory services in developing tropical countries should be explored by the proposed CONSECT. Preparation of special publications required by extension conservation officers in the field should also be emphasized. These officers should be trained (see below) to utilize such publications to advise farmers and prepare displays, thereby insuring continued and regular communication of the conservation message to the farmer.

TRAINING NEEDS

Lack of trained research and extension personnel in soil and water conservation is a major constraint that limits the ability of many tropical countries to meet the above-stated requirements. Aside from regular conferences and workshops that will accommodate the activities of representatives to the proposed coordinating body (CONSECT), two additional major vehicles are needed.

Degree Training of Conservation Officers

The number of research officers in soil conservation in the tropics is far below what is needed to carry out effectively the research and extension functions outlined above. Both undergraduate (for extension-directed personnel) and graduate (for research-directed personnel) degree training are required. A number of U.S. institutions and several in other tropical areas (e.g. India, Malaysia, and Taiwan) can be utilized for this purpose, although some enhancement of specialized capabilities may be required. This training, particularly at the graduate level, should be conducted at academic institutions where research programs in erosion and conservation are sufficiently viable to accommodate thesis and dissertation research. Curriculum offerings must be strong enough to provide the required background. Advisory and extension services must be present to complete the institutional component. Furthermore, the local climate, soils, and vegetation should provide a reasonable representation of tropical conditions.

Non-degree Retraining of Research Officers

Certificate or diploma courses should be offered to conservation officers now engaged in erosion and conservation research in order to facilitate retraining which may be in-country, in-region, or at cooperating U.S. institutions. Existing institutions in developing countries may serve as regional centers (e.g. in India, Malaysia, and Taiwan). The purpose of this training would be to offer refresher courses on design and data processing, to demonstrate techniques, to provide opportunities for exchanging experiences, and to engage trainees in active, ongoing research projects on the various aspects of erosion and conservation. The duration of such training would probably be one year or less.

Non-degree Training of Extension Officers

Certificate and diploma course programs are also needed for currently active extension officers, again with the objective of refreshing and updating skills. Emphasis here should be placed not only on the technical aspects of erosion and conservation trends, but also on the effective display and delivery of information vital to the farmer. Alternative means of stimulating farmer participation in conservation activities should also be included in extension training.

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