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SOIL EROSION FROM TROPICAL ARABLE LANDS AND ITS CONTROL

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I. INTRODUCTION

About 11 million ha of tropical land is developed annually from forest or savanna vegetation for seasonal grain crop production (Eckolm. 1979). The agricultural production of a large portion of this land is liable to be rendered uneconomic by accelerated soil erosion. Not only have vast

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tracts of once biologically fertile land become unproductive (Greenland, 1977; Kovda, 1977; Barney, 1980; Bauer, 1978), but accelerated erosion has caused great environmental damage and become a major pollutant of natural waters (Larson *et al.*, 1983). It is believed that some 1000 million ha of once-forested tropical land has been turned into semidesert during recorded history (Bene *et al.*, 1977). The classic Maya civilization that flourished in humid tropical Central America (what is now Guatemala, Mexico, Honduras, and Belize) is believed to have collapsed because of a decline in soil productivity caused by erosion and soil degradation (Sabloff, 1977). Over-population during the Mayan era led to misuse or overuse of the fragile soil in a stone-technology slash-and-burn agriculture.

In the present age of modern and scientific agriculture, our ability to prevent soil erosion on tropical lands is hardly better than that of the Mayans. Per capita food production has not kept pace with demand in most tropical regions; in Africa it declined by 9.6% between 1970 and 1981. Consequently, more land has been brought under cultivation without serious consideration of the soil's potential and its constraints or of erosion and its long-term consequences. Even some marginal and steep lands normally considered unsuitable for arable land use have been cleared for production of seasonal and annual crops. At the present rate of new land development, it is estimated that about 40% of the remaining forest cover in the humid tropics will be gone by the year 2000 (Barney, 1980).

A considerable body of basic research information on soil erosion in the tropics and its consequences has been accumulated over the past 15 years. The objective of this article is to evaluate, review, and assess the available information, identify knowledge gaps, and define research and development priorities. Only through analysis, collation, and application of this knowledge can the menace of soil erosion be avoided.

II. EROSION HAZARD IN THE TROPICS

There is a lack of standard methodology for assessing the extent of erosion in tropical soils. From the results obtained with methods currently used, it is difficult to generalize about the severity of erosion in different ecologies. Even so, alarming rates of soil erosion are reported throughout the tropics. The absolute quantity of soil eroded (i.e., millimeters of soil lost per year) is quite large, and it causes a more serious decline in crop production than it does in temperate environments. Reconnaissance surveys of global erosion rates were made by Starkel (1972) and Jansson (1982) and for the tropics by El-Swaify *et al.* (1982).

In Africa, soil erosion has been investigated for over 50 years (Armstrong *et al.*, 1980). In the semiarid and Sahel regions of West Africa, lack of adequate vegetation cover in the beginning of the rainy season has caused severe erosion on arable lands (Fauck, 1977). In northern Ghana, Adu (1972) reported a loss of about 0.9 m of soil by sheet and rill erosion. Some severely eroded savanna lands had lost all of the topsoil above the unweathered parent rock. In the Sahel region of central Niger, gullies 150–300 m long usually develop during the one short rainy season (Talbot and Williams, 1978). These gullies terminate on small alluvial fans of 5000–10,000 m^2. A similar type of culturally induced soil erosion is reported in the interior delta of the Niger River in Mali (Barth, 1978). Severe erosion on arable lands in Senegal, Upper Volta, Niger, and Chad has been reported by Fauck (1983). Accidental fires also destroy the scanty vegetation cover of West African savanna woodlands (Afolayan and Ajayi, 1979).

In humid West Africa, deforestation and mechanized farming cause severe soil erosion (Kowal, 1972a,b; Wilkinson, 1975a,b; Lal, 1976; Greenland and Lal, 1977). Erosion is generally of no consequence on forested lands and farmland that is cultivated manually.

Soil erosion has also been intensively investigated in East Africa (Rapp *et al.*, 1972; Rapp, 1975a). Rapp (1975b) reported that annual sediment yields from the semiarid plains of the Dodoma and Arusha Districts in Tanzania are as high as 200–730 $m^3\ km^{-2}$. Christiansson (1978) attributed this high sediment load to excessive grazing and lack of a protective vegetative cover. In another study of semiarid Tanzania, Christiansson (1981) reported high erosion rates, corresponding to sediment yields of 174 to 602 $m^3\ km^{-2}\ year^{-1}$. It is not uncommon to observe annual denudation rates of 1–2 mm, rising to around 100 mm per year on overgrazed and excessively cultivated slopes of highly erodible soils. With the present agricultural system, the soil cover on parts of the slopes may be lost down to the bedrock within 50–100 years. Consequently, the expected life of some reservoirs in the region has been drastically shortened. In Lesotho, Chakala (1981) reported an annual sediment yield of as much as 1800 t km^{-2}. The range of suspended sediment load alone in Lesotho was measured to be 270–1400 t $km^{-2}\ year^{-1}$, and the rates of gully advance may be up to 10 m $year^{-1}$.

In Kenya, Dunne (1977, 1979) and Edwards and Blackie (1981) monitored sediment load from catchments of various sizes and observed that the long-term geologic rate of erosion in these tropical environments for undisturbed catchments is 20–200 t $km^{-2}\ year^{-1}$. The load is excessive, however, for heavily grazed and cultivated catchments. Nyambok and Ongweny (1979) reported severe sheet and gully erosion in the Kamburu/Gtaru hydroelectric dam catchment in Kenya. Studies from Zambia (Robinson, 1978) and Rwanda (Moeyersons, 1981) have shown that erosion becomes severe whenever natural vegetation is modified or removed.

Dhruva Narayana (1983), in a survey of soil erosion in India, estimated that 180 million ha of red earths and Vertisols were loosing 4–43 t ha^{-1} $year^{-1}$ of fertile topsoil by sheet erosion and that an additional 17 million ha were being eroded at the rate of 33–80 t ha^{-1} $year^{-1}$ by gully erosion. The mean sediment load of Indian rivers is 28 t ha^{-1} $year^{-1}$. Murthy and Shankaranarayana (1977) and Singh and Singh (1980) confirmed these findings in their studies of lateritic soils of Siwalics and Meghalaya, respectively, on steep slopes in India. In the hills of neighboring Bangladesh, Islam (1983) reported that surface soil is being lost at the alarming rate of 4 cm $year^{-1}$ on 50% slopes. This amounts to a soil loss of about 500 t ha^{-1} $year^{-1}$. The severity of soil and water loss from arable lands in mainland China has been reported by Lee (1979), Robinson (1979), Gong and Jiang (1979), and Ma and Wang (1981). Severe erosion has been reported in densely populated Java and in the catchment area of the Cimanuk River (Partosedono, 1974). Because of severe erosion in tropical Asia, the sediment load of some Asian rivers is the highest in the world (Douglas, 1968; Jantawat, 1983).

Ahmad and Breckner (1974) reported soil loss as high as 3.8 cm $year^{-1}$ on plowed bare soils on 10–20° slopes in Tobago, West Indies. Ramos and Merinho (1980) reported data from plot measurements in northeastern Brazil indicating soil erosion from a cultivated field as high as 115 t ha^{-1} $year^{-1}$. Suckling (1981) reported accelerated erosion of soils in Sante Catorina. Erosion in the Colombian highlands has been well documented by De Castro (1980). Imeson and Vis (1982) investigated erosion in a Colombian tropical forest along a transect across the Central Andean Cordillera. In this region splash erosion is most damaging. Even soils of volcanic origin, being less permeable to water, generate high water runoff. With cultivation, mass movement and landslides commonly occur. In the Peruvian highlands, Felipe-Morales *et al.* (1977, 1979) reported that erosion considerably exceeds the tolerable range of soil loss. Observations in the Bolivian highlands indicate severe erosion on cultivated and grazed lands (Le Baron *et al.*, 1979). Severe reticular erosion has been reported on an approximately 250,000-ha area south of Lake Maracaibo in Venezuela. High rainfall intensity in the Cuban highlands has led to severe gully erosion (Sagué Diaz *et al.*, 1979; Hernández *et al.*, 1980). This type of erosion generally begins with concentrations of water on sunken foot paths. Arledge (1980), who investigated erosion in the highlands of Guatemala, has reported that about 200,000 farmers hand-cultivate 10 million ha on slopes of up to 80%. The most predominant soils are Andepths, Udalfs, and Rendolls. With maize cultivated up and down the slope, erosion ranges from 200 to 3600 t ha^{-1} $year^{-1}$. Soil loss of 1 to 2 cm $year^{-1}$ is commonly observed on the ash-derived steeplands of El Salvador (Wall, 1981). In Costa Rica, Maroto (1983) reported high erosion rates on the Great Central Plateau, where 80% of the land is severely eroded, and in the Guanacaste Valley, where there is heavy pasture and grain crop production and 74% of the land is severely degraded.

Global maps based on these and other sediment yield data and plot measurements have been prepared for different regions (Jansson, 1982). Fournier (1960) compiled an erosion map based on the suspended sediment yield on catchments exceeding 2000 km^2. Strakhov (1967) produced a world map of erosion rates on the basis of suspended load data from 60 rivers. UNESCO and IAHS (1979) have issued a preliminary global map. The analyses on which these maps are based indicate that tropical regions have much higher erosion rates (>1000 t km^{-2} $year^{-1}$) than temperate regions have. These figures are biased, however, because of a lack of basic data from tropical regions. Detailed regional maps of sediment loss have been prepared only for a few countries in the tropics, such as Cameroon (Olivry, 1977) and northern Ghana (United Nations, 1951). A reconnaissance topsoil loss map of Latin America, prepared by the Conservation Foundation and FAO (1954), shows severe erosion in overgrazed lands of semiarid Mexico and the highlands of Cuba. Cultivation of maize, coffee, and tobacco has also accelerated erosion in Central America, Jamaica, Puerto Rico, and Haiti. Overgrazing is a severe problem in Venezuela, northeastern Brazil, eastern Colombia, and the Andes. Landslides are common in northern Ecuador and central Colombia. Cultivation of maize and other row crops causes severe erosion in the Venezuelan highlands, where 75% of the cultivated area is on slopes exceeding 25%. FAO/UNEP/UNESCO (1980) issued an erosion and degradation map of Africa, the Middle East, and Near East. This map is based on estimates made from the modified universal soil loss equation (USLE); the erosion classes range from <1000 to >20,000 t km^{-2} $year^{-1}$. A similar but more detailed map based on the USLE, prepared for the Kenya rangelands, indicates severe soil erosion (Dunne *et al.*, 1981).

III. EDAPHIC AND CLIMATIC FACTORS IN RELATION TO SOIL EROSION IN THE TROPICS

The consequences of widespread soil erosion in the tropics should be assessed in terms of its effect on crop production and environmental pollution. The effects of soil erosion on crop production depend on many factors, including soil rooting depth, nutrient distribution in the profile, subsoil properties, crop grown, soil and crop management, and the rate of new soil formation.

A. Rate of Soil Formation in the Tropics

The rate of new soil formation is difficult to measure because it depends on many interacting factors, such as parent material, climate, vegetation, and soil disturbance. Dense parent material weathers at a slower rate than that having low bulk density (Harris, 1973). Tropical forests are characterized by intense and deep weathering (Strakhov, 1967). Under ideal soil and climatic conditions, Hudson (1976) estimated the rate of new soil formation to be about 2.5 cm in 30 years. Under normal conditions, however, new soil is formed at the rate of about 2.5 cm in 300 to 1000 years (Olivers, 1971; Pimentel *et al.*, 1976).

Soils of volcanic origin develop faster than those developed on gneiss or basement complex rocks. The rate of new soil formation for Andisols in the humid tropics ranges from 0.06 to 0.73 mm year^{-1} (Ruxton, 1966; Hay, 1960; Van Baren, 1931). In contrast, the rate of new soil formation for Alfisols and Ultisols ranges from 0.001 to 0.007 mm year^{-1} (Table I). Available information suggests that it takes hardly 1 year to lose 1 cm of topsoil, but 1000 years to replace it.

Table I

Rate of Soil Formation in the Tropics

Country	Region	Rate (cm year^{-1})	Soil	Reference
		Soils of volcanic origin		
Indonesia	Humid tropics	0.73	Andisol	Van Baren (1931)
Papua New Guinea	Humid tropics	0.06	Andisol	Ruxton (1966)
Trinidad	Humid tropics	0.46–0.50	Andisol	Hay (1960)
Kenya	Humid tropics	0.14–0.24	Andisol	Dunne *et al.* (1978)
		Residual soils		
Cameroon	Humid tropics	0.007	Alfisol	Boulad *et al.* (1977)
Ivory Coast	Humid tropics	0.013–0.045	Ultisol	Leuneuf and Aubert (1961)
Senegal	Semiarid tropics	0.0013–0.0017	Alfisol	Nahon and Lappartient (1977)
Zimbabwe	Subtropic	0.0011	—	Owens and Watson (1979)
Zimbabwe	Subtropic	0.0041	—	Owens and Watson (1979)
Kenya	Semiarid tropics	<0.1	Alfisol	Dunne *et al.* (1978)

B. Soil Erodibility

Susceptibility to erosion, or soil erodibility, depends on physical, chemical, and biological properties. Contrary to views previously held, soil erodibility is a dynamic property and is readily altered by changes in structural stability, organic matter content, biotic activity, and so on. Soil erodibility, therefore, cannot be easily related to indirect measurements of inherent soil characteristics such as particle size distribution. Many researchers have measured the erodibility of tropical soils using the unit plot technique; others have estimated the *K* factor of the USLE using the nomograph of Wischmeier *et al.* (1971) (Table II; Mota and Lima, 1976).

The predominant soils of the tropics are Oxisols, Ultisols, and Alfisols, in that order of importance. High base status Alfisols cover about 20% of the land area and the low base status about 50%. The data in Table II show that the erodibility of tropical soils varies widely, from practically 0 to as high as 0.67. A similar range of erodibility (*K*) has been reported for soils of the continental United States (Wischmeier and Smith, 1978).

Although numerous investigations have been reported, it is difficult to generalize about erodibility in relation to the predominant soil orders. The difficulties are a lack of standard methodology for assessing erodibility and use of different soil classification systems. Many researchers express erodibility in terms of soil characteristics that can be routinely measured on disturbed soil samples in the laboratory. Others have estimated the *K* factor using a nomogram, even though its applicability to tropical soils is questionable. It is difficult to compare estimates of *K* factor, even from studies carried out on field runoff plots, because the size of the plots and the collection systems differ. The results often depend on the techniques employed.

Erodibility is often related to soil properties such as organic matter content, exchangeable cations, percentage of water stable aggregates, mean weight diameter of aggregates, dispersion ratio, clay ratio, particle size distribution, and free Fe_2O_3 and Al_2O_3 contents (Lugo-López, 1969; Yamamoto and Anderson, 1973; Jungerius, 1975; Kandiah, 1976; Bhatia and Sarmah, 1976; Bhardwaj, 1976; Fetzer, 1977; Sahi *et al.*, 1977; Chandra and De, 1978; Bhola and Jayaram, 1978; Singh and Verma, 1978; Collinet and Valentin, 1979; Laskar and Govindarajan, 1980; Olofin, 1980; Hamblin, 1982). Many researchers attempt to relate laboratory-based indices to field behavior, which is a difficult task indeed. Indices based on analyses of disturbed soil samples do not reflect field behavior under natural rainfall conditions. Futhermore, structural stability or detachability monitored under laboratory conditions is influenced by soil

Table II

Erodibility of Some Tropical Soils

Country	Climatic region	Erodibility (K)	Method[a]	Reference
		Alfisols		
Indonesia	Humid	0.14	E	Bols (1978)
Nigeria	Subhumid	0.06–0.36	M	Lal (1976, 1981a, 1983a)
Nigeria	Subhumid	0.058	M	Wilkinson (1975a)
Nigeria	Semiarid	0.04	M	Vanelslande *et al.* (1984)
Kenya	Subhumid	0.19–0.3	M	Dunne (1977)
Kenya	Subhumid	0.03–0.49	M	Barber *et al.* (1979)
Ivory Coast	Subhumid	0.10	M	Roose (1977a)
Benin	Subhumid	0.10	M	Roose (1977a)
Sri Lanka	Dry zone	0.27–0.35	M	Joshua (1977)
Sri Lanka	Dry zone	0.01–0.31	E	Hasselo and Sikurajapathy (1965)
Senegal	Semiarid	0.25	M	Charreau (1972)
Upper Volta	Semiarid	0.25	M	Roose (1977a)
Tanzania	Semiarid	0.121–0.160	M	Ngatunga *et al.* (1983)
Hawaii	Humid	0.35	M	Dangler and El-Swaify (1976)
		Ultisols		
Sri Lanka	Wet zone	0.17–0.48	E	Joshua (1977)
Thailand	Subhumid	0.09–0.19	M	Tangtham (1983)
Nigeria	Humid	0.04	M	Vanelslande *et al.* (1984)
Nigeria	Humid	0.12–0.48	E	Niger Techno Ltd. (1975)
Hawaii	Humid	0.09	M	Dangler and El-Swaify (1976)
Puerto Rico	Humid	0.004–0.113	M	Barnett *et al.* (1971)
		Oxisols		
Costa Rica	Humid	0.103–0.155	M	Amezquita and Forsythe (1975)
Hawaii	Humid	0.14–0.22	M	Dangler and El-Swaify (1976)
Ivory Coast	Humid	0.10	M	Roose (1977a)
Puerto Rico	Humid	0.01	M	Barnett *et al.* (1971)
Brazil	Subtropics	0.2	E	Freire and Pessotti (1974)
Brazil	Subtropics	0.24–0.27	E	Biscaia *et al.* (1981)
Brazil	Humid	0.017–0.16	E	Ranzani (1980)
		Miscellaneous		
Andisol (Nigeria)	Humid	0.015	M	Vanelslande *et al.* (1984)
Nitosol (Kenya)	Subhumid	0.3–0.5	M	Dunne (1977)
Cambisol (Kenya)	Subhumid	0.5	M	Dunne (1977)
Planosol (Brazil)	Humid	0.25–0.39	E	Ranzani (1980)
Cambisol (Brazil)	Humid	0.11–0.30	E	Ranzani (1980)
Inceptisol (Brazil)	Humid	0.11–0.60	E	Ranzani (1980)
Hydromorphic (Brazil)	Humid	0.15–0.55	E	Ranzani (1980)
Regosol (Sri Lanka)	Wet zone	0.48	E	Joshua (1977)
Typic Dystropepts (Puerto Rico)	Humid	0.017	M	Barnett *et al.* (1971)
Vertic Eutropepts (Puerto Rico)	Humid	0.113	M	Barnett *et al.* (1971)

[a] E, estimated; M, measured.

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moisture potential, ambient temperature, and temperature of impacting water drops (Bruce-Okine and Lal, 1975).

Use of the field rainfall simulator, a definite improvement over laboratory-based indices, is a more rapid and economic technique than field-plot measurements. It has been used in Hawaii (Dangler *et al.*, 1976; El-Swaify and Dangler, 1977; El-Swaify and Cooley, 1977), Brazil (Mondardo *et al.*, 1977; EMBRAPA, 1978), and Africa (Roose and Asseline, 1978; Barber *et al.*, 1979; Collinet and Valentin, 1979). The relationship between field-measured erodibility under natural rainfall conditions and that of spot measurement by the simulator has yet to be established for the diverse soils of the tropics.

Soil erodibility measured on unit plots under natural rainfall conditions changes with time (Lal, 1981a, 1983a). The data in Fig. 1 show that the erodibility of Alfisols in southwestern Nigeria attained the maximum value 3 years after deforestation and subsequently declined. The magnitude of the change in soil erodibility with cultivation depends on management-induced alterations in soil organic matter content, aggregate stability, the rate of sediment removal, and the physical, chemical, and biological properties of the exposed subsoil. The erodibility of soils with high gravel content and skeletal materials in the subsoil decreases with time as a protective desertlike pavement forms on the surface. The necessity of standardizing the methodology is also supported by the data in Fig. 2, which indicate that erodibility decreases with increases in plot size (Lal, 1983b). The exposed subsoil has an important effect on soil erodibility (Machado, 1978). Dangler and El-Swaify (1976) observed that the erodibility of soil derived from similar parent materials at different locations generally varies inversely with prevailing annual rainfall (Fig. 3).

The applicability of Wischmeier's nomogram for estimating the erodibility of tropical soils has not been widely validated. Some researchers have reported the estimated K to be more than that directly measured and vice versa. Wilkinson (1975a) reported the estimated K for an Alfisol in southwestern Nigeria to be about 55% more than that measured. He attributed the low measured erodibility to the presence of gravel and coarse fractions. Ngatunga *et al.* (1983), in a study of three soils in Tanzania, reported that the K factor estimated by the nomogram was lower than the measured value by 44, 45, and 9% on soils with slopes of 10, 19, and 22%, respectively. Data reported by Lindsay and Gumbs in Trinidad also indicate that the nomogram may overestimate soil erodibility (Table III). Vanelslande *et al.* (1984) measured erodibility to be 0.015 at Ikom, 0.04 at Onne, and 0.04 for soils at Jos in Nigeria, compared with estimated K values of 0.039, 0.025, and 0.18, respectively. This nomogram needs to be modified so that it estimates accurately the erodibility of tropical soils. More detailed studies are needed to determine which parameters are strongly related to the erodibility of tropical soils.

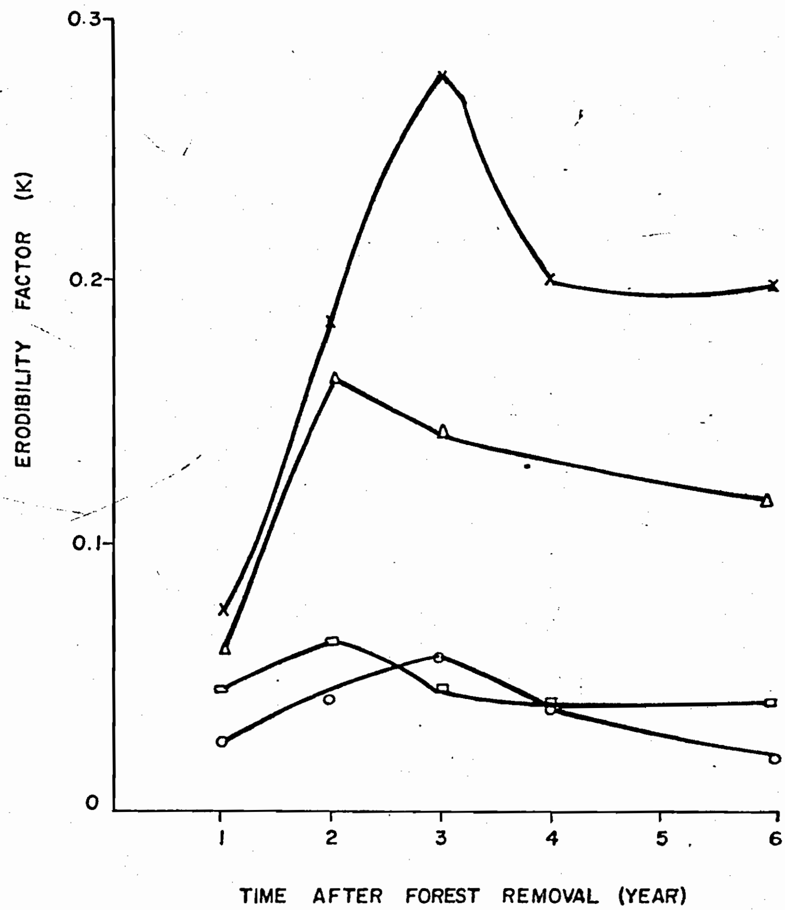

FIG. 1. Changes in erodibility factor (K) of an Alfisol in southwestern Nigeria with time after land clearing and subsequent cultivation, on slopes of 1% (O——O), 5% (×——×), 10% (Δ——Δ), and 15% (□——□). From Lal (1981a).

In spite of these difficulties with methodology, it is evident from the available data that Oxisols and Ultisols have lower erodibility than Alfisols and Inceptisols have (Table II) (Dedecek and Cabeda, 1977). Soils of volcanic origin (Andisols) also have low erodibility. Roose (1974, 1977a,b) evaluated the effects of parent material on soil erodibility. The K value of ferruginous soils on granite (0.20–0.30) is higher than that of ferralitic soils developed on granite, schist, and tertiary sand (0.05–0.18) because the former have lower water permeability and are more susceptible to crust formation—properties that are related to the high contents of silt and fine sand in these soils. Ferruginous soils at Sefa have a low K value because of their low silt and fine-sand fractions. Ultisols and Alfisols

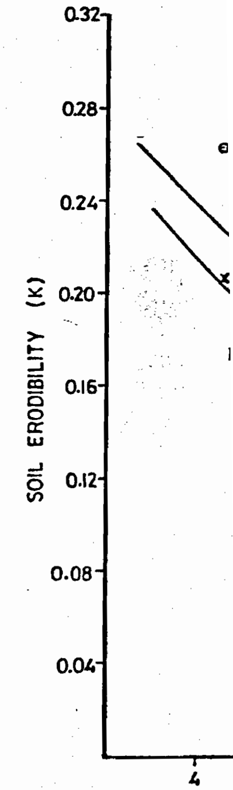

FIG. 2. Effect of
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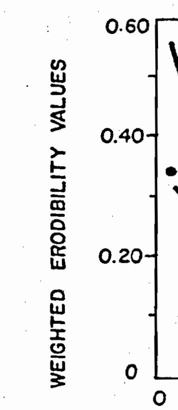

FIG. 3. Effects of
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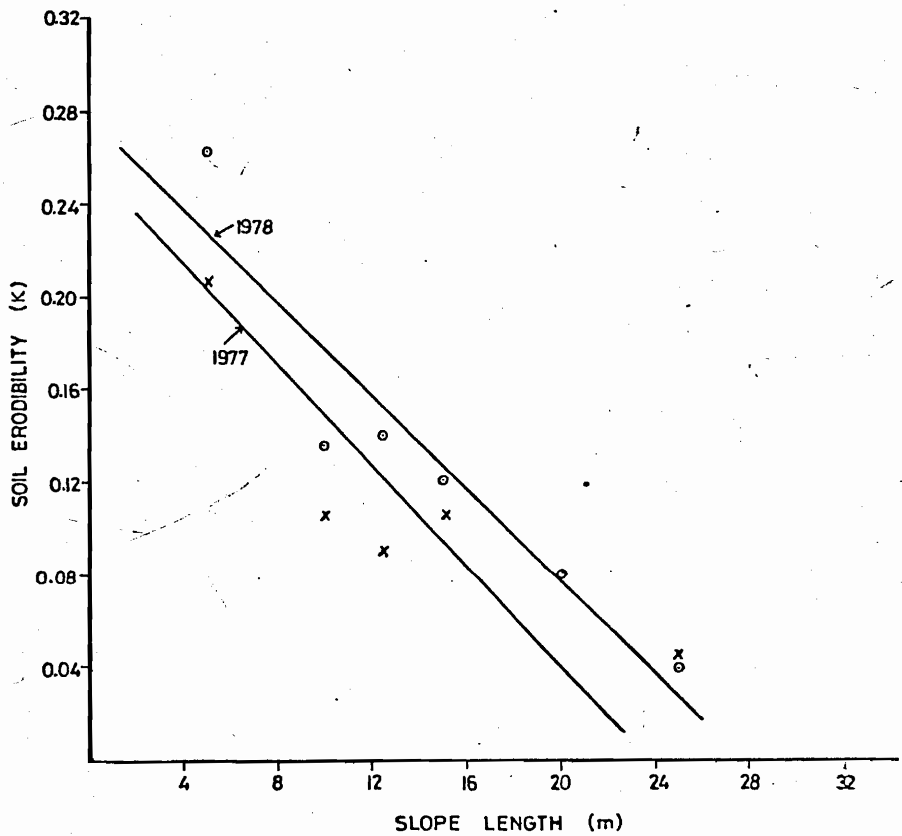

FIG. 2. Effect of slope length on erodibility of an Alfisol at Ibadan, Nigeria. For 1978, $Y = 0.208 - 0.007X$ ($r = 0.89$, significant at 90% confidence level), and for 1977, $Y = 0.276 - 0.010X$ ($r = -0.94$, significant at 95% level). From Lal (1983b).

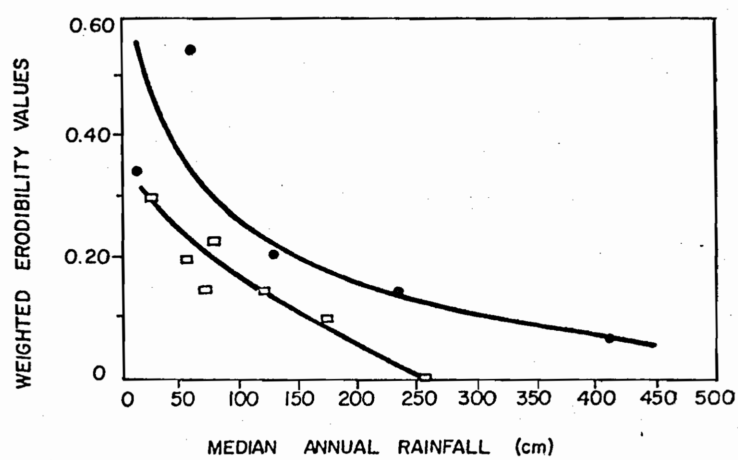

FIG. 3. Effects of annual rainfall amount on erodibility of some soils in Hawaii. Soils from Island of Hawaii (●——●), and soils from Island of Oahu (□——□). From Dangler and El-Swaify (1976).

Table III

Measured and Estimated Erodibility of Some Soils in Trinidad[a]

Soil	Nomogram	Direct measure
Aquic Eutropepts	0.11	—
Tropic Hapludolls	0.07	—
Aquentic Chromuderts	0.14	0.07–0.09
Aquentic Chromudults	0.14	—
Aquentic Chromuderts	0.15	0.06–0.08
Orthoxic Tropudults	0.11	—
Orthoxic Tropudults	0.08	0.04–0.06
Orthoxic Tropudults	0.07	0.03–0.04
Aquoxic Tropudults	0.08	—
Fluventic Eutropepts	0.11	—

[a] According to Lindsay and Gumbs (1982).

developed on coastal sediments and sandstone parent material also have higher K values than have those soils developed on residual and igneous rocks. Wang (1979) studied the erodibility of some steep lands in Taiwan and ranked them in the following order: soils on mudstones > shale–sandstone > slaty shales = soft sandstones = old diluvium > schist = andestic agglomerates > slates = andesites. Potu (1981) estimated erodibility of 24 groups and 10 intergrade groups in Zaire. K ranged from 0.05 to 0.4 for Oxisols and oxic Ultisols. K values for soils developed from sand deposits ranged from 0.05 to 0.1, and those for alluvial deposits from 0.1 to 0.2. Highly erodible soils with K values ranging between 0.2 and 0.4 were those developed from meozoic rocks, sandstones, and quartzites.

C. Climatic Erosivity

Interrill erosion is the detachment of soil by impacting raindrops and transport of it to the rill system by splashing; it is caused to a lesser extent by shallow overland flow. Raindrop impact is the major contributor to soil detachment and to splashing of detached particles. Soil detachment is a complex process that involves changes in the energy level of the soil–water system; the energy required for this process is supplied by impacting raindrops. The amount of soil detached and splashed depends on drop size distribution and rate or intensity of rainfall. The larger the drop and the greater the rainfall intensity, the more the soil splash. The aggressivity or erosivity of the rainfall is therefore its capacity to detach and splash soil particles and can be expressed in terms of drop size, intensity, kinetic energy, or momentum.

1. *Rainfall Intensity and Drop Size*

Tropical rains are generally short, intense storms of relatively high median drop size and high total energy load. The mean rainfall intensity in tropical regions may be two to four times greater than in the northern latitudes. For example, Roose (1971) observed in Abidjan, Ivory Coast, that it is common for 150–200 mm of rain to be received in 24 hr with a sustained intensity of 40 mm/hr. Rains with an intensity of 120 mm/hr sustained for 10 min are often observed, and rainstorms with amounts of 90 and 107 mm received in 24 hr have a return period of 5 and 10 years, respectively. In Kenya, Lawes (1974) recorded 50, 67, and 91 mm of rainfall received during periods of 15, 30, and 60 min, respectively. Dunne and Leopold (1978), who prepared an isohyetal map of Kenya, found that, in tropical areas with high annual rainfall, the rains sustain maximum intensity for 1 hr, with a return period of 2 years. Wilkinson (1975a) and Lal (1976) reported peak rainfall intensities of up to 200 mm/hr in southwestern Nigeria; the most frequent maximum intensity sustained for 30 min (I_{30}) was 2.5–3.8 cm/hr (Fig. 4). High rainfall intensity has also been reported in Zaire (De Ploey, 1971). Kampen (1974) reported intensities of 85–100 mm/hr sustained for 30 min in Hyderabad, India. Ramaiah and Sreenivas (1975) reported I_{30} values of 8.4 cm/hr in the Mysore region of southern India. Rains as intense as 100 mm/hr commonly occur in Sri Lanka (Joshua, 1977). High intensities are also observed in Taiwan and the Philippines (Starkel, 1972). De Castro (1980) reported that in the Colombian highlands rains reach a maximum intensity of 96 mm/hr sustained for 5 min.

The hydrology of countries in the Caribbean is characterized by frequent torrential rains, with an intensity of 140 mm/hr sustained for 40 min (Arenas, 1983).

A median drop size exceeding 2.5 mm is commonly observed in the tropics. Hudson (1976) reported from Zimbabwe that the modal value of drop diameter rose to about 2.5 mm at an intensity of 80–100 mm/hr. In Hawaii, Blanchard (1953) reported a drop size of 2 mm for orographic rains. Kowal and Kassam (1976) observed that the median drop size during some rainstorms in northern Nigeria ranges from 2.34 to 4.86 mm. At Samaru 59% of all drops were found to be larger than 3 mm in diameter. The data in Fig. 5 from southwestern Nigeria indicate that 25% of the rains had a median drop diameter between 2.25 and 2.55 mm, 9% between 2.85 and 3.15 mm, and 14% between 3.50 and 4.30 mm (Lal, 1981b).

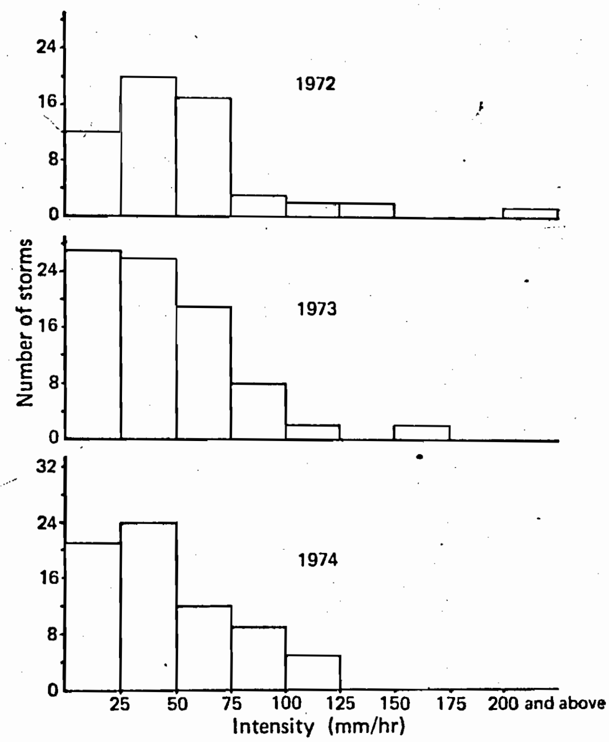

Fig. 4. Frequency distribution of rainfall intensities observed at Ibadan, Nigeria. From Lal (1976).

It is difficult to establish a direct relationship between median drop size (D_{50}) and rainfall intensity unless instantaneous intensity and drop size are monitored simultaneously. The median drop size, calculated for the duration of the storm, and mean rainfall intensity are not necessarily related (Fig. 6).

2. Momentum

On the basis of their work in Uganda and northern Australia, Rose (1960) and Williams (1969) argued that soil detachment and splash are related more to the momentum of rainfall than to its kinetic energy. This is so because momentum is a measure of the pressure or mechanical stress exerted by the rainfall. Empirical relations have therefore been developed that relate rainfall momentum to intensity:

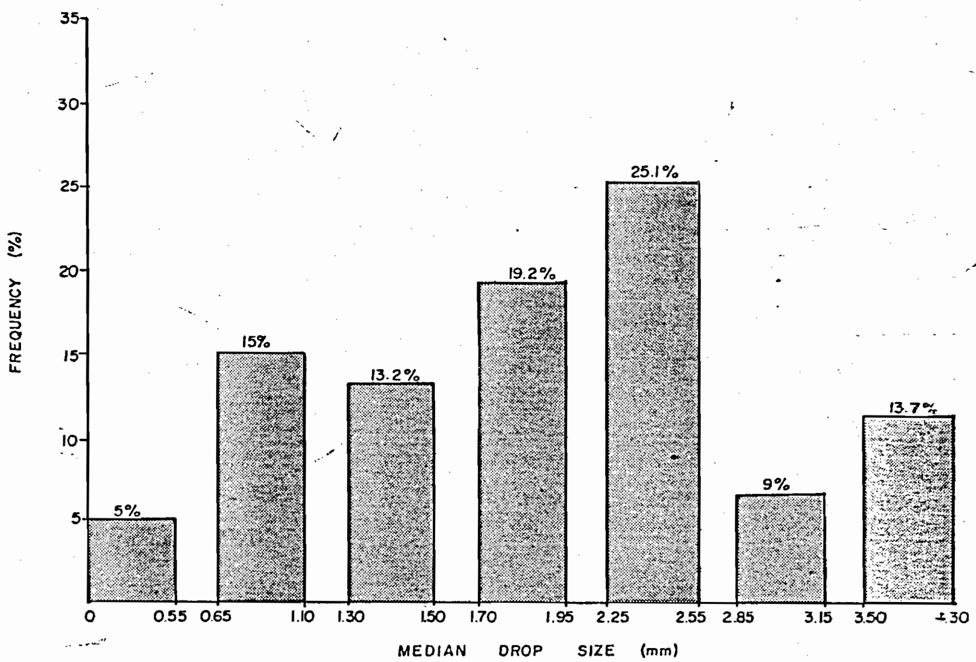

FIG. 5. Drop size distribution of rainstorms recorded at Ibadan, Nigeria. From Lal (1981a).

log momentum (dynes cm^{-2} hr^{-1}) $= 0.711 \log I - 1.461$ (Williams, 1969)

momentum (dynes cm^{-2} sec^{-1}) $= 0.0213I - 0.62$ (Kinnell, 1973)

momentum (J m^{-2} sec^{-1}) $= 6.67P + 9.32$ (Lal, 1981c)

momentum (J m^{-2} sec^{-1}) $= 4.79I + 8.74$ (Lal, 1981c)

where I is rainfall intensity (cm/hr) and P is rainfall amount (cm).

3. *Kinetic Energy*

Many researchers feel that the kinetic energy of rainfall is more closely related to its capacity to cause splash than to its momentum. Rainstorms with energy loads of 70–100 J m^{-2} mm^{-1} are commonly observed in the

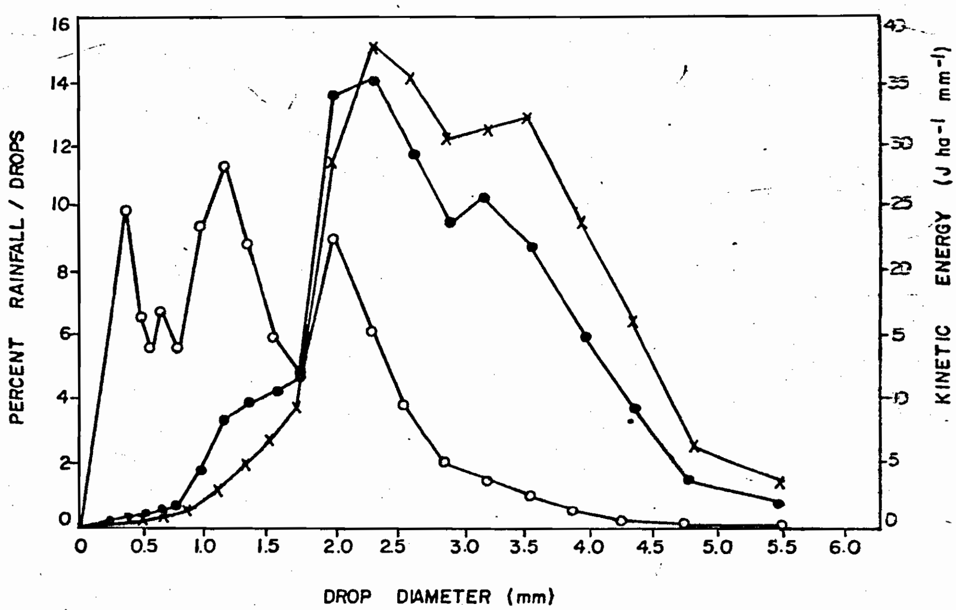

FIG. 6. Median drop size (O——O), rainfall intensity (●——●), and energy load (×——×) of a rainstorm received at Ibadan, Nigeria. From Lal (1983d).

tropics. Hudson (1976) computed that the annual energy load of most rains in the temperate zone is 900 J/m², compared to 16,800 J/m² for the tropics. Similarly, Kowal and Kassam (1976) reported that the energy loads of rains in northern Nigeria were much higher than those reported from subtropical Zimbabwe by Elwell (1972, 1978), and by Elwell and Stocking (1975). Attempts have been made to relate kinetic energy (*KE*) to easily monitored parameters such as rainfall amount and intensity:

KE (ergs cm^{-2} sec^{-1}) $= 8.37I$ (Kinnell, 1973)

KE (ergs cm^{-2} sec^{-1} mm^{-1}) $= Z(1 - be^{-hI})$ (Kinnell, 1981)

KE (t m ha^{-1}) $= (198 + 84 \log_{10} I)P + 24$ (Wilkinson, 1975a)

KE (ergs cm^{-1}) $= (41.4P - 120.0) \times 10^3$ (Kowal and Kassam, 1976)

KE (J m^{-2}) $= 18.846P$ (Elwell, 1979a,b)

KE (J m^{-2})

KE (J m^{-2})

where I is rainfall
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Computation of

KE (J m^{-2}) $= 24.50P + 27.6$ (Lal, 1981c)

KE (J m^{-2}) $= 18.2I_{30} + 18.2$ (Lal, 1981c)

where I is rainfall intensity in cm/hr, P is rainfall amount in mm, I_{30} is a maximum intensity of 30 min, and Z, b, and h are empirical constants.

4. *Estimation of Erosivity*

Rainfall parameters directly related to splash and erosion are difficult to monitor routinely. Attempts have therefore been made to relate rainfall erosivity to practical parameters such as intensity, amount, and duration.

Among the most widely used methods is the R factor (EI_{30}) of the USLE (Wischmeier *et al.*, 1958). In addition, Hudson (1976) developed $KE > 1$ index for Zimbabwe, and Lal (1976) found that soil loss from individual storms is related to a compound factor AI_m. Wilkinson (1975a) developed an empirical equation relating the EI_{30} index to the time (t) taken to attain peak rainfall intensity:

$$EI_{30} = 18e^{-0.18t} + 4.0$$

Similarly, Roose (1977b) developed a regression equation relating the EI_{30} index to the annual rainfall amount for many locations in West Africa. For the monsoon rains from June to September, a linear equation was obtained: $EI_{30} = 0.5P_{annual} + 0.05$. A logarithmic relation, however, was obtained for inland stations in Ivory Coast, Upper Volta, Senegal, Niger, Chad, Cameroon, and Malagasy. Based on these indices, isoerodent maps have been prepared for many tropical regions. In Africa, isoerodent maps have been prepared for Benin (Aalders, 1976; Anastase, 1977), Nigeria (Ajunwon, 1981; Armon, 1983), Zaire (Poto, 1979), and Africa (Roose, 1977b). An isoerodent map based on the EI_{30} index has also been compiled for India (Ramaiah and Screenivas, 1975; Singh and Verma, 1975; Babu *et al.*, 1978), Malaysia (Maene *et al.*, 1975), and Java (Bols, 1978). Rainfall erosivity for various regions of Brazil has been computed by Bertoni and Pastana (1964), Pereira *et al.* (1978), Freire and Castro Filho (1977), and EMBRAPA (1978). Elsewhere in the tropics, the EI_{30} index has been computed for Costa Rica (Amezquita and Forsythe, 1975), Hawaii (Lo *et al.*, 1983), Uruguay (Koolhaas, 1979), Chile (Brito and Peño McC., 1980), and Venezuela (Paez *et al.*, 1983). The annual R index (metric units) ranges from 200 to 3500 in Africa, 200 to 1500 in India, 200 to 600 in Uruguay, and 200 to 300 in the Andean foothills of Chile.

Computation of isoerodent maps on the basis of any empirical index is of relatively minor importance (Kinnell, 1973) because it is difficult to estimate the erosive power of rainfall reliably from meteorological observations. The problems of using the EI_{30} index in the tropics have been documented by Hudson (1976), Ahmad and Breckner (1974), and Lal (1976). Although energy-based parameters (especially if energy is computed on the basis of equations developed for the tropics) are the most accurate predictors of rainfall erosivity, as measured in terms of splash or soil loss, reliable estimates can also be obtained from the average annual or daily rainfall. Since in many parts of the tropics there are no recording rain gauges, it is difficult to obtain information about high-intensity, short-duration rainfalls. Elwell and Stocking (1973, 1975) and Stocking and Elwell (1976) observed that the long-term average annual soil loss can be predicted from average annual rainfall. Furthermore, their studies in Zimbabwe indicate that there is little difference between momentum, energy, and rainfall depth as predictors of soil loss from plots under some vegetation cover or of runoff from both bare and covered plots. Kinnell (1973) reported that kinetic energy and momentum are similarly related to rainfall intensity. The amount of rainfall can therefore be a practical predictor of erosion. Measurements of sand splash by natural rains at Ibadan indicated that there is a linear relationship between rainfall amount and intensity (Lal, 1981c). The correlation coefficient[1] was identical with both parameters.

$$S = 17.6I_{30} + 1.6 \qquad (r = 0.84^{**})$$

$$S = 22.7P + 19.7 \qquad (r = 0.84^{**})$$

where S is sand splash (g/m^2), I_{30} is maximum rainfall intensity sustained for 30 min (mm/hr), and P is the rainfall amount (mm). The rainfall amount or the intensity or both can be more practical predictors of soil erosion than energy parameters, particularly if the equations for computing energy parameters are not developed in the tropics.

The energy load and drop size distribution of tropical rains need to be characterized. The common practice of applying values for rainfall parameters at one geographical location based on rainfall characteristics observed at another can lead to gross inaccuracies in estimating soil loss (Kinnell, 1973). Empirical relations are greatly influenced by rain types and geographical locations, and they must be validated for the particular location before they can be used there to estimate soil erosion.

[1] **, Correlation coefficients were significant at the 95% level.

IV. COMPARISON OF SOIL EROSION IN TROPICAL AND TEMPERATE CLIMATES

For similar soils and topography, the magnitude of soil erosion is greater in the tropics than in temperate regions, even in primary forest (Birot, 1968). The reasons are that (1) the soil horizon that is rich in organic matter is thinner and the organic matter declines rapidly because of high rates of mineralization, (2) the rains are more frequent and more intense, with higher energy loads, and (3) soils are generally structurally unstable, tend to slake and disperse, and reduce infiltration. Highly weathered tropical soils with nonswelling, low-activity clays are often found on steep slopes that are easily dispersed and are particularly susceptible to splash. The lack of soil organic matter content and the presence of structurally inactive iron oxides in some soils make them susceptible to crust formation (Greenland, 1977). The crust encourages overland flow that quickly leads to rill and gully erosion. Lack of a silt fraction in some tropical soils and a high amount of quartz and skeletal materials make these soils structurally inert (Bridges, 1970; Lal, 1978).

High temperatures throughout the year affect soil erosion both directly and indirectly. They cause rapid mineralization of soil organic matter, adversely affecting soil structure and other biotic activity. High temperatures also increase evapotranspiration, thereby decreasing surface runoff. Some of the specific effects of high temperatures are described in the following paragraphs.

1. Soil Erodibility. High temperatures accelerate soil drying between showers. Dry soil of extremely low moisture potential can be structurally unstable and is highly erodible because of structural collapse resulting from sudden release of entrapped air or heat evolved during sudden wetting (Collis-George and Lal, 1971, 1973).

High water temperature also increases the ability of rain to disrupt soil aggregates. The data in Table IV show that the number of drops required at a water temperature of 50°C to disrupt a soil aggregate were considerably less than that required at 30°C (Bruce-Okine and Lal, 1975). Furthermore fewer drops were required to disrupt an aggregate at high soil pF than at low soil pF. An effect similar to that of high temperature results when the water temperature is low but the soil aggregates are heated.

2. Erosivity. The absolute viscosity of water is lower at high temperatures than at low temperatures. Low viscosity causes high velocity gradients in the rill system and increases the water shear stress of lower water layers of the laminar flow. High shear stress therefore increases the de-

Table IV

Effect of Soil Moisture Potential (pF) and Water Temperature on Number of Drops Required to Disrupt an Aggregate[a]

Soil	pF	Average number of drops at different temperatures		
		30°C	40°C	50°C
A_1	4.44	194	173	143
A_2		86	65	34
A_3		48	37	36
A_1	7.00	21	19	11
A_2		14	11	10
A_3		17	14	11

[a] From Bruce-Okine and Lal (1975).

tachment and transport capacity of overland flow (Grissinger, 1966). A decrease in dynamic viscosity at high water temperatures decreases its dampening effect on turbulent flow. Increases in turbulence facilitate transport of suspended particles. The net effect of increases in turbulence on carrying capacity is difficult to assess because settling velocity also increases with decreases in dynamic viscosity.

3. *Surface Cover*. Because of their rapid drying rate and low soil organic matter content, tropical soils lack effective vegetation cover at the beginning of the rainy season. This is particularly noticeable in regions where the dry season is longer than 4 months. The problem is further aggravated if the soils are saline or acidic. Dry and hot soils without vegetation cover suffer from severe erosion at the onset of high-intensity monsoons. Erosion is therefore more severe in regions with marked seasonal variations in rainfall distribution. Tropical wet–dry regimes have more severe erosion than equatorial climates with less seasonal variability in their hydrothermal regimes (Williams, 1969; Wilson, 1973).

V. SLOPE CHARACTERISTICS AND SCALES OF MEASUREMENT

The effects of slope characteristics (length, gradient, and aspect) on runoff and soil erosion are not well understood, and there is not yet enough data from which one can draw valid conclusions. Yet, this information is essential for designing mechanical erosion control measures such as terraces, diversion channels, and waterways. Since these measures are expensive to install and maintain, their adaptation and design should be based on widely validated basic research data.

An increase in slope gradient generally increases soil erosion. The effect of slope gradient on erosion is, however, drastically influenced by slope aspect, surface characteristics, and crop residue management. The data in Table V show that slope gradient had no effect on erosion when the soil was mulched at a rate of 6 t ha^{-1} of crop residue (Lal, 1976). Gumbs and Lindsay (1982) also reported that there is no relationship between slope gradient and erosion of an Orthoxic Tropudult planted to maize and cowpea (Table VI). More research information is needed from the tropics before any generalizations can be made about the effects of slope steepness on soil erosion.

The effect of slope length on water runoff and soil erosion is strongly influenced by slope gradient and soil physical properties such as particle size distribution. A few studies conducted in the tropics indicate that slope length has a negative effect on water runoff per unit area. For example, the data in Table VII show that, compared to a 5-m slope length, the annual cumulative runoff was 66, 49, and 35% for 10-, 15-, and 20-m slope lengths, respectively. The correlations and regression equations relating runoff to slope length and slope steepness indicate the following relationships:

$$W = 773L^{-0.53} \qquad (r = 0.99)$$

$$W = 857.1 + 12.5S - 11.2L - 0.7LS \qquad (r = 0.81)$$

where W is annual runoff (mm), S is slope gradient, and L is slope length.

The data in Table VIII indicate that slope lengths between 5 and 20 m

Table V

Effect of Slope Gradient on Soil Erosion for Two Systems of Soil Surface Management[a]

Slope (%)	Soil erosion (t ha^{-1} $year^{-1}$): Bare fallow	Soil erosion (t ha^{-1} $year^{-1}$): Maize with maize mulch
1	11.2	0.0
5	156.2	0.0
10	232.6	0.2
15	229.2	0.0
Mean erosion	157.3	0.05

[a] From Lal (1976).

Table VI

Effect of Slope Gradient on Soil Erosion of an Orthoxic Tropudult in Trinidad[a]

Slope (%)	Soil erosion (t ha^{-1})	
	Bare uncultivated	Cultivated in maize
11	27.9	8.3
22	14.7	1.6
52	42.1	4.3

[a] Adapted from Gumbs and Lindsay (1982).

Table VII

Effect of Slope Length and Steepness on Runoff[a]

Slope length (m)	Runoff (mm) on slopes of different steepness				Mean runoff (mm)
	1%	5%	10%	15%	
5	187.8	578.5	508.0	403.3	419.4
10	245.3	288.8	302.7	265.7	275.6
15	188.2	231.7	189.9	205.9	203.9
20	96.4	165.7	160.3	164.8	146.8
Mean runoff (mm)	179.5	316.1	290.2	259.9	

[a] From Lal (1983b).

Table VIII

Effect of Slope Steepness and Length on Soil Erosion[a]

Slope length (m)	Soil erosion (t ha^{-1} year^{-1}) on slopes of different steepness				Mean erosion (t ha^{-1} year^{-1})
	1%	5%	10%	15%	
5	4.5	143.4	219.1	190.7	139.4
10	2.8	94.5	229.6	212.4	134.8
15	6.5	117.4	235.8	288.5	162.1
20	2.2	52.0	163.5	306.0	130.9
Mean erosion t ha^{-1} year^{-1}	4.0	101.8	212.0	249.5	

[a] From Lal (1983c).

had less effect on soil erosion than slope gradient. There was either no consistent trend in soil erosion per unit area or the erosion decreased with increases in slope length (Lal, 1983c). Furthermore, slope length and slope gradient interacted with erosion. For steep gradients of 10 and 15%, increases in slope length of 5 to 15 m raised soil erosion per unit area. On a 15% slope, relative soil erosion was 1, 1.11, 1.51, and 1.60 for 5-, 10-, 15-, and 20-m slope lengths, respectively. Regression equations relating slope length to erosion for different slope gradients are shown in Table IX. For gentle slope gradients of 1 and 5%, slope lengths between 5 and 20 m had only a slight or no effect on soil erosion per unit area. Less erosion takes place on long slopes of gentle gradient than on short slopes because on the former there is more deposition of large particles.

The sediment concentration (i.e., the carrying or transport capacity of water runoff) increases linearly with increases in slope length (Table X). For example, the soil erosion : runoff ratio was 1, 1.27, 1.50, and 1.99 for 5-, 10-, 15-, and 20-m slope lengths, respectively. In comparison, the erosion : runoff ratio increases logarithmically with increases in slope gradient (Table X).

In experiments on cane fields in Trinidad, Georges (1977) observed that larger plot lengths (6 and 8 m) produced significantly less erosion than shorter plot lengths (1, 2, and 4 m). In the United States, Mutchler and Greer (1980) also reported that the magnitude of the slope length exponent depends on slope gradient. For low slope gradients of 0.5% and less, the value of slope length exponent was as low as 0.15. Experiments conducted at Oahu, Hawaii on residual soils for slope lengths of 24 and 11 m indicated that the slope length exponent is 0.67, 0.76, and 1.1 for slopes of 4, 9, and 15%, respectively (Dangler *et al.*, 1976). These results are contrary to those reported by Lal (1983b,c) and indicate that slope length has a strong effect on soil erosion.

Table IX

Regression Equations Relating Soil Loss to Slope Length[a]

Slope (%)	Regression equation[b]
1	$A = 5.7L^{-0.15}$
5	$A = 305.1L^{-0.47}$
10	$A = 280L^{0.12}$
15	$A = 97L^{0.39}$

[a] From Lal (1983c).
[b] A = Soil erosion (t ha^{-1} $year^{-1}$). L = slope length (m).

Table X

Effect of Slope Steepness and Length on Erosion: Runoff Ratio[a]

Slope length (m)	Erosion: runoff ratio ($t\ ha^{-1}\ mm^{-1}$) on slopes of different steepness				Mean ratio ($t\ ha^{-1}\ mm^{-1}$)
	1%	5%	10%	15%	
5	0.024	0.248	0.431	0.473	0.294
10	0.011	0.327	0.759	0.799	0.474
15	0.035	0.507	1.242	1.403	0.797
20	0.023	0.314	1.020	1.857	0.804
Mean ratio $t\ ha^{-1}\ mm^{-1}$	0.023	0.349	0.863	1.133	

[a] From Lal (1983c).

In interpreting data on the effects of slope length on runoff and soil erosion, one must also consider the nature of the slope or its aspect (i.e., whether it is regular, convex, or concave). Soil loss from irregular slopes depends on the steepness of a short section of the slope immediately above the point of measurement. For example, if the rill system breaks down at the bottom of a concave slope, resulting in sheet flow and sediment deposition, there is less soil loss than if the slope had been convex or concave. As shown in Table XI, for 12.5-m slope length, water runoff from a 10% regular slope was 16% more than that from a 19.2% concave slope. The soil erosion, however, was 2.25 times greater from the regular

Table XI

Effect of Slope Aspect on Water Runoff and Soil Loss on Bare Plowed Soil[a]

	12.5 m long		37.5 m long	
	10.0%	19.2%	9.3%	13.4%
	a. First season, 1974			
Runoff (mm)	320.7	260.4	175.6	157.3
Soil erosion ($t\ ha^{-1}$)	77.3	34.6	114.3	68.6
	b. Second season, 1974			
Runoff (mm)	162.4	140.7	52.3	52.7
Soil erosion ($t\ ha^{-1}$)	32.3	14.0	40.2	26.8
Slope	Regular	Concave	Convex	Complex

[a] From Lal (1976).

slope than from a concave slope of the same length and double the gradient (Lal, 1976). A similar comparison for a 37.5-m slope length indicates that a 9.3% convex slope had 8.5% more water runoff and 62% more soil loss per unit area than a plot of the same length with a 13.4% complex slope.

The agronomic implications of these findings are discussed in the section on slope management. The data raise questions about methodology and the effects of the scale of experimentation on the results. The size of the drainage basin studied has an important effect on sediment and water yields. Water loss through infiltration on long slopes decreases runoff, reduces transport capacity, and promotes deposition. The problem of scale in the interpretation of data has been discussed for Sierra Leone by Millington (1981). Experiments were also conducted in Australia by Ciesiolka and Freebairn (1982) on catchments of three sizes: 0.2, 1. and 250 ha. The results showed that peak runoff rates declined rapidly with increased catchment size. Sediment concentration was also much lower in the 1.0-ha catchment than in the 0.2-ha rill outlet, although there was less of a difference in sediment concentration between the 1- and 250-ha catchments. The choice of scale for an experiment should therefore be based on the intended use of the data. The scale should be such that the experimental results are relevant to small and large landholders.

VI. DEFORESTATION AND CHANGE IN LAND USE

Dense vegetation cover and leaf litter protect the soil against raindrop impact. The low sediment load from tropical forests is partly due to the protective effect of the forest cover (Holeman, 1968; Douglas, 1968; Oyebande, 1981). The annual sediment load is 18–37 t km^{-2} $year^{-1}$ for Congo, and 67–87 t km^{-2} $year^{-1}$ for the Mahanadi and 1500 t km^{-2} $year^{-1}$ for the Damodar rivers in India. A litle soil erosion occurs under forest cover as a result of slope wash and soil creep processes. Rill erosion can take place in a primary forest with high rainfall because of the heavy stem flow, which has enough energy to cause rill development (Birot, 1968). In regions of exceptionally high rainfall, considerable runoff can occur under forest cover (Bonell and Gilmour, 1978; Bonell *et al.*, 1979). Sediment yield under these conditions depends on many factors: soil characteristics, topography, and amount and distribution of rainfall. Erosion under dense undisturbed perhumid and seasonally humid forest is usually about 1 t ha^{-1} $year^{-1}$ (Roose, 1979).

A. Deforestation

Deforestation drastically alters the water balance (Pereira, 1973). Sediment cores obtained from the Black Sea indicate that even in a gentle climate, deforestation and agriculture have accelerated soil erosion by a factor of 3 during the last 1800 years (Degens *et al.*, 1976). The exposed soil fluctuates widely in soil temperature and moisture regime, its organic matter content declines rapidly, and its structure and macropores are adversely affected (Seubert *et al.*, 1977; Lal and Cummings, 1979). In tropical South America, Ramos and Merinho (1980) measured soil erosion to be 115.4, 8.6, and 1.2 t ha^{-1} from bare plowed, herbaceous vegetation, and shrub and tree cover treatments, respectively. Runoff was 52, 26, and 18%, respectively. Similar experiments in the Bolivian highlands (Le Baron *et al.*, 1979), French Guyana (Roche, 1981), and Venezuela (Blancaneaux and Araujo, 1982) indicate that deforestation disturbs the soil–water–forest ecosystem and accelerates soil erosion.

The effects of deforestation on water balance and soil erosion in tropical Asia are similar to those observed in South America. In Mindanao, Philippines, Kellman (1969) observed that the runoff rates in a 10-year-old abaca plantation were twice as high as in natural mixed dipterocarp forest, 4 times as high as in a newly cleared rice field, and about 50 times as high as in a rice field cleared 12 years before. Leigh (1973, 1982) reported that about 400,000 ha of forest was cleared in peninsular Malaysia under the 5-year plan ending in 1975. The erosion on forested land was 336 kg ha^{-1} $year^{-1}$, compared to 6730 kg ha^{-1} $year^{-1}$ from tea plantations and 10,090 kg ha^{-1} $year^{-1}$ from arable land. From 1950 to 1980, the forest cover on the tropical island of Hainan, China, has decreased from 50 to 21%. Out of a total area of 33,900 km^2, only 11% is now under natural forest cover (Wangcheng, 1983). Many studies in Java and Sumatra also indicate that erosion from agricultural soil is accelerating rapidly, even though terraces have been installed (Thijsse, 1977a,b; Van Der Linden, 1978; Kronfellner-Kraus, 1980). Deforestation and cultivation of agriculturally unsuitable lands result in severe and extensive soil erosion. In Papua New Guinea, erosion is observed only on about 30% of the land from which forest has been removed (Klaer and Löffler, 1980). On the western coast of southern India, Chinnamani (1977) observed that erosion from a poorly managed tea plantation was as much as 40 to 50 t ha^{-1} $year^{-1}$, compared to 0.06 t ha^{-1} $year^{-1}$ from forested land. In Hong Kong, Lam (1978) reported that the suspended sediment discharge from three catchments of about 0.25 km^2 each was 2422, 1682, and 55 t $year^{-1}$ for completely cleared, partially cleared, and uncleared catchments, respectively.

The effects of change in land use on soil erosion have been investigated

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Effects of Meth

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Manual clearing/ conventional/tillage
Shear blade clearing/no tillage
Tree pusher–root rake/no-tillage
Tree pusher–root rake/conventional tilla

[a] Land was cleared in 197
[b] T, Unmeasurable trace.

for many regions in Africa—in Tanzania by Rapp (1977) and Christiansson (1978), in Zambia by Robinson (1978), in Kenya by Pereira (1973), in Madagascar by Rossi and Salomon (1979). In Ivory Coast, Roose (1979) observed that water runoff and erosion were 50 and 1000 times greater from cleared land than from forested land. Erosion from arable lands was as high as 20–90 t ha^{-1} $year^{-1}$, compared with only 20–450 kg ha^{-1} under forest.

The effects of various methods of deforestation and subsequent management on runoff and erosion in 3- to 4-ha watersheds at IITA, Ibadan have been reported by Lal (1981b). The data in Table XII indicate that deforestation, method of land clearing and development, and tillage system significantly affect runoff and erosion. A forested catchment in the transitional subhumid zone of West Africa, with dense undergrowth and thick leaf litter, had virtually no storm runoff and soil wash between 1978 and 1981. A little localized soil movement was occasionally observed during heavy rainstorms, but no erosion of any consequence was monitored for the entire watershed. The catchment that was partially cleared and on which traditional farming was practiced also registered minimal runoff and soil loss. Among the management treatments involving complete clearing followed by mechanized farming, the manually cleared plots lost, over a

Table XII

Effects of Methods of Deforestation and Postclearing Soil Management on Runoff and Erosion from an Alfisol[a]

Treatment	Basin area (ha)	Runoff (mm)		Soil erosion (t ha^{-1})	
		1979	1979–1981	1979	1979–1981
Forest	15	T[b]	T	T	T
Traditional farming	2.6	3.0	6.6	0.01	0.02
Manual clearing/no-tillage	3.1	16.0	16.1	0.4	0.4
Manual clearing/conventional/tillage	3.2	54.0	79.7	5.0	9.8
Shear blade clearing/no tillage	2.7	86.0	104.8	4.0	4.8
Tree pusher–root rake/no-tillage	3.2	153.0	170.0	15.0	15.7
Tree pusher–root rake/conventional tillage	4.0	250.0	330.6	20.0	24.5

[a] Land was cleared in 1979. Crop rotation schedule from 1979 to 1981 was maize–cassava–maize–cowpea.
[b] T, Unmeasurable trace.

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period of 3 years, a total of 48 mm of runoff and 5 t ha^{-1} of soil, compared to 201 mm of runoff and 15 t ha^{-1} of soil lost from the mechanically cleared plots. For treatments in which similar tillage systems were used, runoff and soil erosion from no-till watersheds averaged, over a period of 3 years, 97 mm and 7 t ha^{-1}, respectively, compared to 205 mm and 17 t ha^{-1} for conventionally plowed and terraced watersheds. The effects of deforestation method on runoff and erosion were more pronounced in the first year after land clearing (Table XII). The land clearing and management system that best conserved the soil was manual clearing, followed by no-tillage. Soil erosion and runoff from shear blade clearing were also within acceptable limits. The sediment load in the machine-cleared plots was much greater than in the manually cleared plots. Both runoff and sediment density in the no-till treatments were much lower than in the conventionally plowed and terraced watersheds. Soil degradation caused by mechanical clearing can be drastically reduced, however, through subsequent management—seeding cover crops and adopting appropriate tillage methods for growing seasonal crops through the mulch cover of the suppressed sod (Wilson and Lal, 1982).

B. Land Use

Changes in land use—for example, making land on which forest or perennial crops are grown into arable and grazed pastures—increase soil erosion. In northern Nigeria, Kowal (1972a,b) observed negligible runoff under natural vegetation cover but maximum runoff from cropped land. In Kenya, Pereira (1973) reported that, when land that had been natural forest was made into a tea plantation, the risk of runoff and erosion was lower than if it had been made into arable land. By the time the tea bushes had developed a complete canopy, the water balance was virtually unchanged from that of natural forest. On arable land, soil structure deteriorated, as indicated by the results of the rainfall acceptance test: 0.94, 0.89, 0.91, and 0.75 over 4 years of cultivation (Pereira *et al.*, 1954).

The effects of changing land use on sediment load in catchments of different sizes have been reported by Dunne (1979) and Edwards and Blackie (1981). Dunne (1979) analyzed the sediment yields from 61 Kenyan catchments and observed that the long-term geologic rate of erosion in these tropical environments for undisturbed catchments is between 20 and 200 t km^{-2} $year^{-1}$. Dunne's (1979) report indicates that grazed and agricultural catchments yield more sediment than those that are partially or completely under forest cover. The variations in sediment yield from agricultural catchments are related to relief, amount of rainfall, soil erodibility, and other physical factors. The regression equations relating sediment yield to runoff and relief for different land uses are shown below.

1. For forested catchment:

$$SY = 1.56Q^{0.46}S^{-0.03} \qquad (R^2 = 0.98)$$

$$SY = 2.67Q^{0.38} \qquad (R^2 = 0.98)$$

2. For forest > agriculture:

$$SY = 1.10Q^{1.28}S^{0.047} \qquad (R^2 = 0.76)$$

3. For agriculture > forest:

$$SY = 0.14Q^{1.48}S^{0.51} \qquad (R^2 = 0.74)$$

4. For rangeland:

$$SY = 4.26Q^{2.17}S^{1.12} \qquad (R^2 = 0.87)$$

where SY is the mean annual sediment yield (t km^{-2} year^{-1}), Q is mean annual runoff (mm), and S is relief (dimensionless). Including the topographic variable for the forested catchment did not significantly influence the explained variance.

In the Caribbean, Alleyne and Percy (1966) observed more runoff from catchments in which pineapples were grown than from those with the original vegetation cover. Studies of the Colombian rain forest zone indicate that there is less runoff and a lower sediment load from forest than from grassland and field sites (McGregor, 1980). Fearnside (1980), in reporting on the effect of various land uses in the Trans-Amazonian Highway colonization area of Brazil, arranged the uses in the following order according to severity of erosion and water runoff loss associated with them: arable land > pasture > plantation crops > secondary forest > primary forest.

The importance of providing effective ground cover for erosion control was also underscored by studies from northern (Bhola *et al.*, 1975) and western India (Chinnamani, 1977). In Thailand, Virgo and Ysselmuiden (1979) developed guidelines for cultivation of steep lands on the basis of slope steepness. Irrespective of slope, less soil was lost from grassland than from coffee or bare fallow plots (Fig. 7). Land with slopes exceeding 7° are recommended only for semiperennial or plantation crops that provide a permanent ground cover. In the wet zone of Sri Lanka, Krishnarajah (1983) observed dramatic differences in soil erosion among different land uses: 0.05, 38, and 70 t ha^{-1} year^{-1} for perennial–garden crops, capsicum, and tobacco fields, respectively. Experiments conducted at

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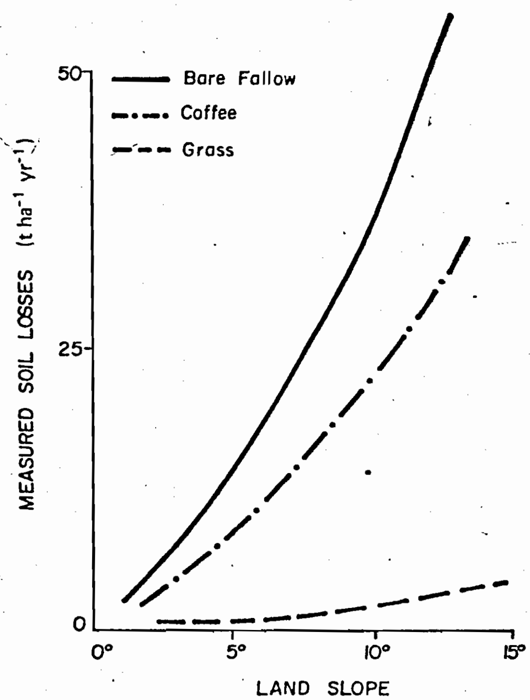

FIG. 7. Effect of land use on soil erosion from steep lands in Thailand. From Virgo and Ysselmuiden (1979).

China's Xiaoliang Experiment Station (1977), which is in a tropical monsoon climate, indicated that sediment loss decreased from 15,000 to 2945–4400 $m^3\ km^{-2}$ after perennial vegetation cover was established on an eroded catchment. In the subtropics of northeastern Australia, Cassells *et al.* (1982) observed that stream flow and sediment levels increased only during the initial plantation establishment phase. The only exception to this pattern was a single catchment, where plantation establishment without cultivation had no measurable effect on the stream sediment regime. Pressland and Fisher (1982) concluded, on the basis of studies in New South Wales, Australia, that the land use, particularly as defined by the type of vegetation, is instrumental in determining the quantity and rate of sediment discharge. Both the foliage and roots of vegetation are important in attenuating catchment discharge.

All the available data support the conclusion that in the humid and subhumid tropics erosion is most severe on arable lands or excessively grazed pastures. Pereira *et al.* (1967) concluded from investigations of grass leys on a lateritic red soil in Kenya that the trampling caused by 20 yearling beasts on 1 acre for 2 days produced severe runoff, even from a paddock that was completely covered by a dense mat of stolons and foliage. Paddock grazed 2 days prior to the storm lost half as much, and no flow was observed from paddock grazed 5 days earlier.

Agroforestry, the practice of growing seasonal crops and leys in association with woody perennials, can maximize output without increasing the risk of soil erosion (Mongi and Huxley, 1979). A combination of deep-rooted perennials and shallow-rooted annuals should decrease water runoff and maintain an ecological balance (Lundgren, 1980; Lundgren and Nair, 1983).

VII. SOIL EROSION AND CROP PRODUCTIVITY

The effects of soil erosion on crop yield depend on soil profile characteristics, the crop, and the prevailing micro- and mesoclimate. For soils that support deep root systems and have edaphically favorable subsoil properties, loss of surface soil essentially represents a loss of nitrogen and other nutrients. Although the cost of production is increased and there is other off-site damage to crops and environments, the crop yield is hardly affected. The addition of fertilizers can compensate for the loss of nitrogen in eroded soil. Not many soils in the tropics, however, possess these favorable properties. The majority of tropical soils have edaphically inferior subsoil and shallow effective rooting depth. Consequently, crop yield declines drastically as surface soil thickness is reduced. The loss of the surface layer cannot be compensated for by additional inputs. Soil mismanagement can readily lead to irreversible soil degradation. Between these two extremes are soils of medium effective rooting depth and surface soil thickness. Although loss of surface soil can partly be compensated for by addition of fertilizers, the symptoms of erosion often remain undetected because they are masked by the effects of improved technology. The longer it takes to recognize the symptoms, the more difficult it becomes to restore soil productivity.

In most tropical soils, the nutrient reserves are often concentrated in the thin surface horizon. Soils with low-activity clays are generally of low inherent fertility and have low nutrient and water retention capacity. In addition to creating nutrient imbalance, drought stress adversely affects crop growth on eroded soils, even in the humid and subhumid regions. Because crop yield is an integrated response of many interacting factors, it is difficult to establish a one-to-one cause–effect relationship between rates of erosion and crop yield. Erosion is a selective process of preferential removal of organic matter and the clay fraction. The enrichment ratio of eroded sediments is usually 3:5 for organic matter content, clay fraction, and concentration of different plant nutrients (Lal, 1976). The removal of a unit of soil depth may, in an edaphic sense, have adverse effects of several orders of magnitude.

There is little research information about the effects of erosion on soil productivity loss in tropical environments. In Malaysia, Huat (1974) reported that maize yield declined sharply after artificial removal of 15 and 30 cm of soil. The drastic decline was attributed to loss of plant nutrients (Siew and Fatt, 1976). In a study of Alfisols in West Africa, Lal (1976) reported a maize yield reduction of 23% after 2.5 cm of soil (Oxic Paleustalf) was artificially removed near Ibadan, Nigeria. Rehm (1978) reported that in Cameroon the removal of 2.5 cm of topsoil caused a 50% drop in maize yield and that the exposed subsoil became completely unproductive when 7.5 cm of soil was removed. The effects of artificial soil removal on maize yield on a Tropeptic Eutrustox in Hawaii were reported by Yost *et al.* (1983), who indicated that the loss of 35 cm of topsoil could not be compensated for by any amount of commercial fertilizer because root growth in compacted subsoil was severely curtailed. Mbagwu *et al.* (1983) studied the effects of topsoil removal on maize and cowpea grain yield with variable rates of nitrogen and phosphorus application on an Ultisol in southeastern Nigeria (Onne) and two Alfisols in southwestern Nigeria (Ikenne and Ilora). The data in Table XIII indicate that maize grain yield was more drastically reduced than that of cowpea. After removal of 5, 10, and 20 cm of soil, and at 120 kg ha^{-1} N and 30 kg ha^{-1} P ($N_{120}P_{30}$), maize grain yield was reduced by 82, 94, and 100% of the uneroded control at Onne; 25, 76, and 86% at Ikenne; and 31, 81, and 97% at Ilora. None of the fertilizer combinations used was an effective substitute for topsoil on the Ultisol at Onne. For some Alfisols, however, nitrogen rates of 60 and 120 kg ha^{-1}, in combination with 30 kg ha^{-1} of phosphorus, were able to restore productivity on soils from which 5 cm of topsoil had been removed. In contrast, the removal of 5 cm of topsoil caused the following yield reductions in cowpea: 15% for a Ultisol at Onne and 15% and 26% for Alfisols at Ikenne and Ilora, respectively. In another desurfacing study on an Alfisol near Ibadan, Nigeria, Lal (1983e) observed that the depth of soil removed had a significant effect on maize grain yield (Table XIV). The desurfaced soil did not respond to different rates of nitrogen and phosphorus. The infertility of exposed subsoils of some Ultisols and Oxisols in Puerto Rico was attributed to deficiency of phosphorus and zinc and to a reduction in the amount of available water reserves (Ritchey and Fox, 1974).

In a study of variable soil erosion under natural rainfall conditions on field plots, Lal (1981a) reported an exponential decline in grain yield of maize and cowpea with increases in cumulative soil erosion (Table XV).

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Table XIII

Effects of Depth of Topsoil Removed and of Nitrogen and Phosphorus Fertilizer Applications on Maize and Cowpea Grain Yields[a]

Crop	Fertilizer levels[b]	Onne				Ikenne				Ilora			
		0	5 cm	10 cm	20 cm	0	5 cm	10 cm	20 cm	0	5 cm	10 cm	20 cm
Maize[c] yield, (Mg ha^{-1})	N_0P_0	0.43	0.02	0.02	0.00	4.92	3.42	1.30	0.32	2.18	0.60	0.38	1.01
	$N_{60}P_{15}$	0.75	0.10	0.01	0.16	5.91	4.27	1.23	1.31	2.89	2.29	0.59	0.51
	$N_{120}P_{30}$	1.68	0.12	0.09	0.00	6.20	5.94	1.76	1.00	3.89	2.22	0.54	0.07
Cowpea[d] yield, (kg ha^{-1})	N_0P_0	557	208	164	177	773	762	316	270	1623	931	1085	317
	$N_{60}P_{15}$	218	321	209	151	778	670	673	473	1515	1237	764	631
	$N_{120}P_{30}$	234	301	302	123	695	464	791	261	1985	1062	802	633

[a] After Mbagwu *et al.* (1983).
[b] Numerical subscripts on N and P refer to rates of application in kg ha^{-1}.
[c] $LSD_{0.05}$ (least significant difference at the 95% confidence level) for maize yields (Mg ha^{-1}):

site	soil depth (*D*)	fertilizer (*F*)	$D \times F$
Onne	0.20	0.28	0.56
Ikenne	0.84	0.68	1.36
Ilora	0.65	0.57	1.15

[d] $LSD_{0.05}$ for cowpea yields (kg ha^{-1}):

site	soil depth (*D*)	fertilizer (*F*)	$D \times F$
Onne	132	72	143
Ikenne	247	183	366
Ilora	222	187	373

Table XIV

Effects of Soil Removal Depth on Maize Grain and Stover Yield for an Alfisol near Ibadan, Nigeria[a]

Soil removal depth (cm)	Grain yield ($t\ ha^{-1}$)	Stover yield ($t\ ha^{-1}$)
0	2.0	4.2
10	0.7	2.6
20	0.2	1.9
$LSD_{0.05}$	0.6	0.6

[a] From Lal (1983e).

Maize grain yield was also significantly (negative) correlated with leaf concentration of manganese. Maize leaves from eroded plots had more manganese than those from less eroded or uneroded plots. Analyses of soil physical and chemical properties indicated that soil quality declined with increases in erosion. Multiple regression analysis of maize grain

Table XV

Soil Loss: Crop Yield Relationships for Cowpea and Maize[a]

Slope (%)	Regression equation[b]	Correlation coefficient[c] (r)
	Cowpea	
1	$Y = 0.43 \exp(-0.036X)$	−0.85*
5	$Y = 0.64 \exp(-0.006X)$	−0.97**
10	$Y = 0.49 \exp(-0.004X)$	−0.91*
15	$Y = 0.29 \exp(-0.002X)$	−0.66
	Maize	
1	$Y = 6.41 \exp(-0.017X)$	−0.99**
5	$Y = 6.70 \exp(-0.003X)$	−0.99**
10	$Y = 6.70 \exp(-0.003X)$	−0.89**
15	$Y = 8.36 \exp(-0.004X)$	−0.86*

[a] From Lal (1981a).
[b] Y, Grain yield ($t\ ha^{-1}$); X, soil erosion ($t\ ha^{-1}$).
[c] *, Significant at the 90% confidence level; **, significant at the 95% level.

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$Y = 1.79 - 0.0$

where Y is maize
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yield with four variables indicated that the changes in soil properties brought about by erosion have a significant effect on maize grain yield:

$$Y = 1.79 - 0.007E + 0.70\text{OC} + 0.07M_0 + 0.002I_c \qquad (r = 0.90)$$

where Y is maize yield (t ha^{-1}), E is soil erosion (t ha^{-1}), OC is organic carbon (%), M_0 is total porosity (%), and I_c is infiltration capacity (cm).

Lal (1983e) compared the effects of natural erosion and desurfacing on maize grain yield. The rate of decline in maize grain yield caused by natural erosion was 0.26 t ha^{-1} mm^{-1} of eroded soil. Artificial removal of soil for 10 and 20 cm of soil reduced yield at rates of 0.13 and 0.09 t ha^{-1} cm^{-1}.

VIII. SOIL LOSS TOLERANCE

Tolerable soil loss is the maximum rate of erosion that will permit sustained crop productivity economically and indefinitely. The soil loss limits most commonly used in selecting appropriate land uses and soil and crop management practices range from 2.5 to 12.5 t ha^{-1} $year^{-1}$, depending on soil characteristics. Soil erosion should be considered serious if land productivity cannot be restored, even with improved systems of management. Erosion should also be low enough that off-site damage is kept to a minimum and erosion control measures, such as terraces and diversion channels, are not subjected to excessive silting. According to Stamey and Smith (1964), a tolerable rate of soil loss must (1) provide for permanent preservation or improvement of the soil, (2) be adaptable to the erosion and renewal rates of any soil characteristics, (3) be site specific, (4) be independent of the agencies that cause erosion, and (5) allow depletion of any soil characteristic that is excessive. At this rate the root zone should be maintained at an optimum depth for a range of crops, and the rate of soil formation should balance the rate of erosion. Skidmore (1979) developed a usable mathematical function for computing tolerable soil loss:

$$T(x,y,t) = T_1 + [(T_2 - T_1)/2] + \cos[(T_2 - T_1)/2] + [(Z - Z_1)]$$

where $T(x,y,t)$ is a tolerable rate of soil loss at point (x,y), T_1 and T_2 are lower and upper limits of allowable soil loss rate (T_1 corresponds to soil renewal rate), Z_1 and Z_2 are minimum allowable and optimum soil depths, and Z is the present soil depth.

Information on soil loss tolerance for most tropical soils is not available. Bertoni *et al.* (1975) estimated the soil loss tolerance of some central

Brazilian soils to be as low as 4.5 t ha^{-1} $year^{-1}$. Krishnarajah (1983) used a soil loss tolerance of 9 t ha^{-1} $year^{-1}$ for some soils in the wet zone of Sri Lanka. Lal (1983e) used Skidmore's (1979) method to compute tolerance levels of some soils on a toposequence in southwestern Nigeria (Fig. 8). The data presented indicate that, for soils with a gravel and concretionary horizon at shallow depths beneath the soil surface, the amount of acceptable soil loss ranges from a low of 0.05 t ha^{-1} $year^{-1}$ to a maximum of 2 t ha^{-1} $year^{-1}$. These estimates are highly biased by the importance given the few centimeters of surface horizon and are based only on the productivity decline caused by erosion, without consideration of the off-site damage. It seems from this analysis that the currently used rates of 12.5 t ha^{-1} $year^{-1}$ are far too high for fragile tropical soils with low inherent fertility. More research information is needed for different soils to evaluate the effects of soil erosion on the productivity of tropical crops in different management systems.

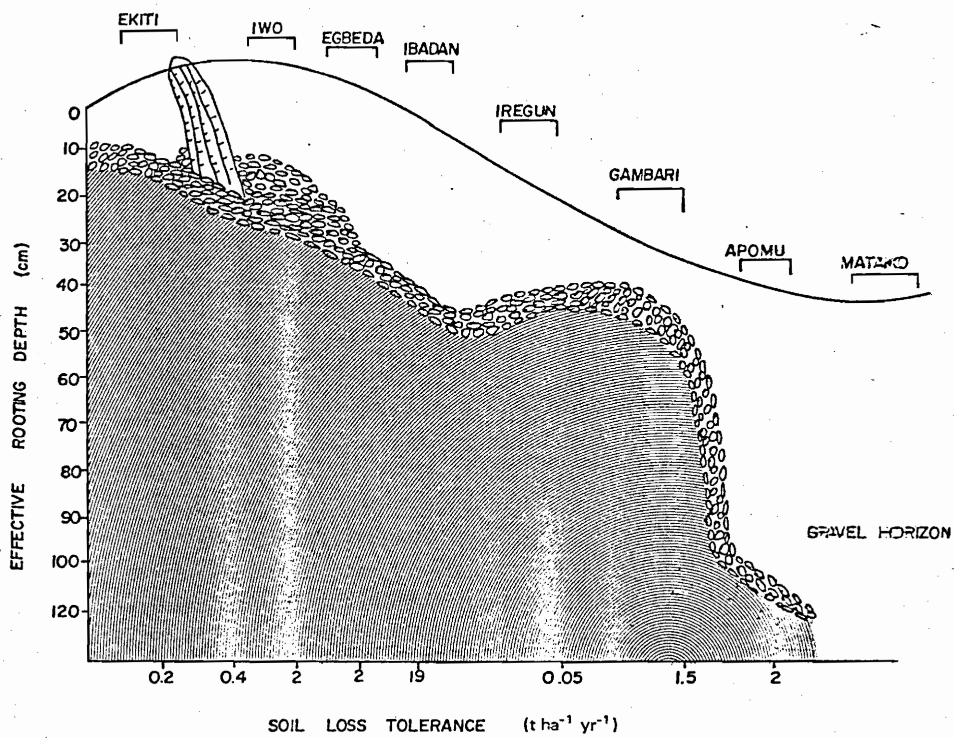

Fig. 8. Soil loss tolerance of different soil series developed along a toposequence in southwestern Nigeria. Note the relation between soil loss tolerance and depth of the gravelly horizon. From Lal (1983e).

IX. BASIC PRINCIPLES OF EROSION CONTROL: PREVENTIVE VS. CONTROL MEASURES

Accelerated soil erosion is a symptom of land misuse and soil mismanagement. Choosing an appropriate land use should drastically curtail and even prevent accelerated soil erosion. A hydrological and energy imbalance in the soil–climate–vegetation equilibrium, resulting from a change in land use, is what generates excessive water runoff, degenerates soil structure, and accelerates soil erosion. Erosion will not be severe if the unproductive original vegetation can be replaced with a more productive land use without seriously altering the delicate ecological balance that exists in an undisturbed environment. That is why soil erosion is not serious with traditional land uses; they preserve the ecological balance (Young, 1977).

The basic aims of runoff management and soil conservation include (1) prevention of soil detachment by raindrop impact, (2) improvement of the structural stability of the soil surface and its water retention and transmission properties, and (3) reduction of the runoff rate and its velocity by providing appropriate surface drainage systems that channel water safely and allow it more time to infiltrate. All these measures prevent soil splash and improve soil-water receptivity. If the cultivation of erosion-prone land to seasonal crops cannot be avoided, then soil management techniques that prevent direct raindrop impact on a bare soil surface should be used. These techniques can be divided into two groups: (1) those that help keep water infiltration rates high enough to reduce runoff to a negligible level, and (2) practices that permit safe disposal of runoff water from the field when rainfall exceeds the infiltration capacity of the soil.

The choice of techniques depends on many factors. Cultural practices that maintain a high infiltration rate include mulch farming, use of crop cover, and conservation tillage systems. Curative measures for safe disposal of water runoff include a range of engineering techniques, including land shaping, construction of contour bunds, and diversion channels. From the results of 500 annual erosion measurements at 20 stations in West Africa, Roose and Lelong (1976) and Roose (1977a,b) concluded that biological methods of soil conservation based on practices that maintain a high infiltration rate and prevent raindrop impact are much more suitable for West Africa than costly engineering techniques designed for safe disposal of runoff. Soil erosion is a problem that should be tackled by better means of water conservation within the soil profile itself. The relative merits and demerits of these methods are discussed in Sections X and XI.

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X. SOIL SURFACE MANAGEMENT FOR EROSION CONTROL

Soil surface management techniques that have an important influence on soil erosion include seedbed preparation, crop residue use, weed control, and crop husbandry (including fertilizer application, time of planting, plant population, and pest control). The long-term objective of soil surface management is to preserve, restore, and sustain soil productivity and maintain ecosystem stability. Its immediate objectives are to optimize biophysical environments and alleviate soil-related constraints. Good soil surface and crop management practices are crucial in controlling runoff and erosion. An erosion-promoting, open-row crop such as maize can be grown without causing serious erosion provided that a soil management technique that helps maintain the infiltration rate of the soil is adopted. There is no substitute for "good farming." What constitutes good farming, however, differs among soils, crops, and ecologies.

A. RESIDUE MULCH

The importance of crop residue mulch in soil and water conservation is widely recognized. Maintaining a layer of crop residue mulch on the soil surface is a particularly valuable means of maintaining the capacity of the soil to accept high intensity rainfalls and of preventing splash. Mulch protects the crop against raindrop impact just as dense vegetation cover does. Residue mulch placed between tea bushes controls erosion even on steep slopes in Sri Lanka (Manipura, 1972), East Africa (Shaxson, 1975, 1981; Othieno, 1975; Othieno and Laycock, 1977), and Colombia. In Barbados, mulches are used to control erosion on disturbed lands and to encourage revegetation for land restoration (Eavis *et al.*, 1974). Contour planting and mulches are recommended for erosion control on steep lands in Guatemala (Arledge, 1980). Residue mulch is recommended for erosion control in cane fields in Taiwan (Liao, 1972) and Trinidad (Ahmad, 1977) and in orange plantations on steep lands in Taiwan (Liao and Chang, 1974). In Chile, Peña MacCaskill (1978, 1981a,b) reported that 1 and 2 t ha^{-1} of straw applied on a moderately eroded silt loam soil with 11% slope reduced runoff by 24 and 50%, compared with unmulched plots. Soil loss was 35, 8.8, 4.1 t ha^{-1} $year^{-1}$ with 0, 1, and 2 t ha^{-1} of straw, respectively.

Roose (1975) and Roose and Asseline (1978) demonstrated that mulching in pineapple plantations in Ivory Coast (Table XVI) was the most effective means of combating erosion. In the Sudano-Sahelian plains of northern and central Ivory Coast, Collinet and Valentin (1979) concluded

Table XVI

Effect of Residue Management on Soil Erosion in Pineapple Plantations in Ivory Coast[a]

Slope (%)	Soil erosion (t ha^{-1}) with different residue management methods				Soil erodibility (K)
	Bare soil	Residue burnt	Incorporated	Mulch	
4	15	0.2	0.03	0.0001	0.06
7	102	3.8	0.06	0.000	0.12
20	253	16.7	9.7	0.007	0.07

[a] Adapted from Roose and Asseline (1978).

that straw mulching is the only technique that is entirely effective in maintaining high infiltration and providing soil protection. Mensah-Bonsu and Obeng (1979) concluded from plot measurements at Kumasi, Ghana, that, compared with bare fallow, mulching reduced runoff by factors of 11–35 and erosion by factors of 188–750. Soil erosion from plowed bare soil ranged from 100 to 313 t ha^{-1} $year^{-1}$. Lal (1976) reported an exponential decline in runoff and soil erosion with an increase in mulch rate from 0 to 6 t ha^{-1} for soils ranging in slope from 1 to 15% (Table XVII). The effectiveness of crop residue mulch, however, depends on soil properties, the predominant slope and the ground cover. In addition to preventing raindrop impact, mulch improves soil structure by enhancing biotic activity, such as that of earthworms (Table XVIII).

Table XVII

Regression Equations Relating Soil Erosion with Slope for Different Mulch Rates[a,b]

Mulch rate (t ha^{-1})	Regression equation[c]	Average soil loss (t ha^{-1})
0	$A = 11.8S^{1.13}$	76.6
2	$A = 0.5S^{0.87}$	2.4
4	$A = 0.07S^{1.07}$	0.37
6	$A = 0.01S^{1.0}$	0.09

[a] From Lal (1976).

[b] Under natural rainfall, from field plot of an Alfisol near Ibadan, Nigeria.

[c] A, Soil erosion (t ha^{-1}); S, slope (%).

Table XVIII

Effects of Mulch Rate on Soil Physical Properties[a]

Property	Regression equation[b]	Correlation coefficient[c] (r)
Percentage water-stable aggregates (>0.5 mm)	$Y = 42 + 7.36X - 0.41X^2$	0.98**
Dispersion ratio	$Y = 26.9 \exp(-0.09X)$	0.97**
Erosion ratio	$Y = 71.9 \exp(-0.09X)$	0.96**
Earthworm activity (casts m^{-2} $month^{-1}$)	$Y = 1.41X + 2.66$	0.98**

[a] Adapted from Lal *et al.* (1980).
[b] X, Mulch rate (t ha^{-1}).
[c] **, Significant at the 95% level.

B. Cover Crops and *in Situ* Mulch

Frequent use of cover crops in rotation is recommended to provide ground cover quickly and protect steep slopes from accelerated soil erosion. Fallowing with appropriate cover crops is also important in restoration of eroded and degraded lands (Lal *et al.*, 1978, 1979).

A variety of creeping and low-growing legumes are recommended for erosion control on steep land in Malaysia (Soong and Yap, 1976). Liang (1978) demonstrated that a legume covering 60% or more ground surface (Table XIX) drastically reduced runoff and erosion on a 10% slope in

Table XIX

Runoff and Soil Erosion from a 10% Slope at Different Stages of Legume and Grass Cover in Peninsular Malaysia[a]

Treatment	Ground cover at different growth stages: 5–30% Runoff (mm)	5–30% Erosion (t ha^{-1})	60–90% Runoff (mm)	60–90% Erosion (t ha^{-1})	>90% Runoff (mm)	>90% Erosion (t ha^{-1})
Bare	56.9	13.5	70.8	30.2	64.3	11.2
Legume cover	46.9	9.0	18.8	1.8	2.4	0.09
Natural cover	3.6	0.01	3.5	0.005	1.4	0.06
Rainfall (mm)	269		311		287	

[a] From Liang Ah Hong (1978).

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peninsular Malaysia. In Taiwan, Wang *et al.* (1975) recomended the use of *Paspalum notatum, Desmodium buergeri,* or weeping love grass for steep slopes of 25°. Jean and Juang (1979) also recommended *Paspalum notatum* for ground cover and reported that it has favorable effects on soil structure and aeration. Cover crops are widely used in India (Chatterjee and Maiti, 1974; Jha and Rathore, 1981). Bajpai *et al.* (1975) observed that grass and legume covers control erosion on slopes of up to 4%. Improvement of soil cover is a widely practiced method of soil and water conservation in the Philippines (Landencia, 1972), Somalia (Hassan, Mohamed, 1979), and the tropics (Humphreys, 1982).

Some important cover crops for soil and water conservation in the tropics and their growth habits have been described by Okigbo and Lal (1977). When necessary these cover crops can be suppressed by chemical or mechanical means (Wilson *et al.*, 1982) so that seasonal crops can be grown through them. The dry weight of residue mulch from some of these crops can be as much as 11.0, 6.5, 13.0, and 10.0 t ha^{-1} $year^{-1}$ for *Psophocarpus palustris, Glycine wightic, Centrosema pubescens, and Pueraria phaseoloides,* respectively (Wilson, 1979). Although the residue of legumes decomposes more rapidly than that of grasses, there is generally enough for a successful seasonal crop without excessive erosion. Cover crops that have been found suitable for different ecological regions in the tropics are listed in Table XX. The hydrographs of 5-ha twin watersheds, with and without a cover of *Mucuna utilis* at Ibadan, Nigeria (Fig. 9), indicate its effectiveness in runoff control.

C. No-Till Farming

Methods of seedbed preparation that involve both primary and secondary mechanical tillage, including moldboard plowing and harrowing, expose soil to the harsh tropical climate and increase the risk of wind and water erosion. Soil detachment and splash are directly proportional to the soil surface exposed. Although mechanical tillage may improve water storage for the first few rains, it subsequently encourages runoff and erosion by splash and surface crusting (Collinet and Valentin, 1979). The merits of a no-till system in biostructurally active soils have been documented for some tropical ecologies (Lal, 1983a). No-tillage has been shown to create a favorable soil temperature regime and improve soil structure by preventing slaking and raindrop impact for soil and water conservation. These benefits are to a large extent attributable to the crop residue mulch.

For some Oxisols and Ultisols in Indonesia, Suwardjo and Abujamin

Table XX

Some Cover Crops Used for Soil and Water Conservation in the Tropics

Cover crop	Country of use	Reference
Grasses		
Axonopus micay	Colombia	Perea Rivas (1983)
Brachiaria brizantha	Sri Lanka	Roberts (1981)
Brachiaria decumbens	Colombia	Perea Rivas (1983)
Brachiaria mutica	Philippines	Pacardo (1983)
Cenchrus ciliaris	Venezuela	Paez *et al.* (1983)
Eragrostis curvua	Sri Lanka	Manipura (1972)
Panicum antidotala	India	Bajpai *et al.* (1975)
Panicum coloratum	Kenya	Thomas (1975)
Paspalum notatum	China	Jean and Juang (1979)
Paspalum conjugatum	Malaysia	Liang (1978)
Pennisetum purpureum	India	Bajpai *et al.* (1975)
Legumes		
Centrosema pubescens	Philippines, Malaysia	Pacardo (1983); Liang (1978)
Desmodium buergeri	China	Wang *et al.* (1975)
Mucana pruriens	West Africa	Okigbo and Lal (1977)
Phaseolus aconitifolius	India	Bajpai *et al.* (1975)
Psophocarpus palustris	West Africa	Okigbo and Lal (1977)
Pueraria phaseoloides	Colombia	Perea Rivas (1983)
Stizolobium deeringianum	Nigeria	Wilson and Lal (1982)
Stylosanthes guianensis	Sri Lanka	Manipura (1972)
Vigna catjang	India	Bajpai *et al.* (1975)

(1983) observed that the no-till system kept soil erosion within tolerable limits. Soil erosion on an Oxisol was 500, 200, and 15 t ha^{-1} $year^{-1}$ for plowed bare, plowed cropped, and no-till cropped treatments, respectively. In Brazil, Benatti *et al.* (1977) reported that for Lotosol Roxo on a 6.3% slope loss of water was identical in no-till and plowed plots but that soil loss decreased by 20% with the no-till system (Table XXI). Vieira *et al.* (1978) reported that reduced tillage and no-tillage methods controlled approximately 75% of the 13–14 t ha^{-1} of soil loss that occurred with conventional tillage. Cassol and Eltz (1980) recommended a no-till system for cultivation of maize on hill slopes. Peña MacCaskill (1981a,b) found that leaving crop residue on the soil surface reduced soil losses by 42%, compared with conventional plowing. In Parana, Brazil, Derpsch (1981) and Kemper and Derpsch (1980–1981) demonstrated that the no-till system controls erosion efficiently. In Trinidad, Gumbs and Lindsay (1982) observed in the northern mountain range that no-tillage reduced runoff and soil loss on an Orthoxic Tropudult in which maize and cowpea were

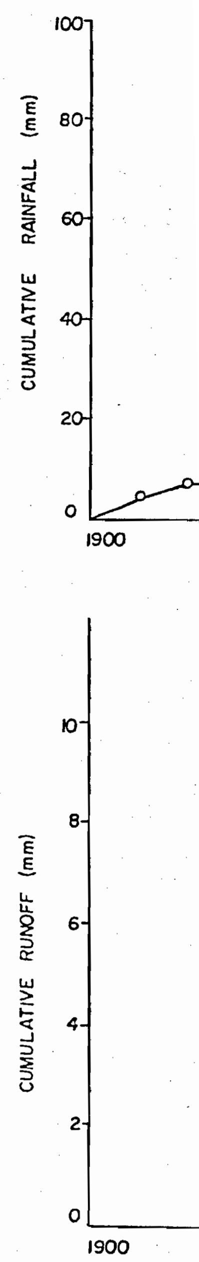

FIG. 9. Rainf
southwestern Ni
28 August, 1982.

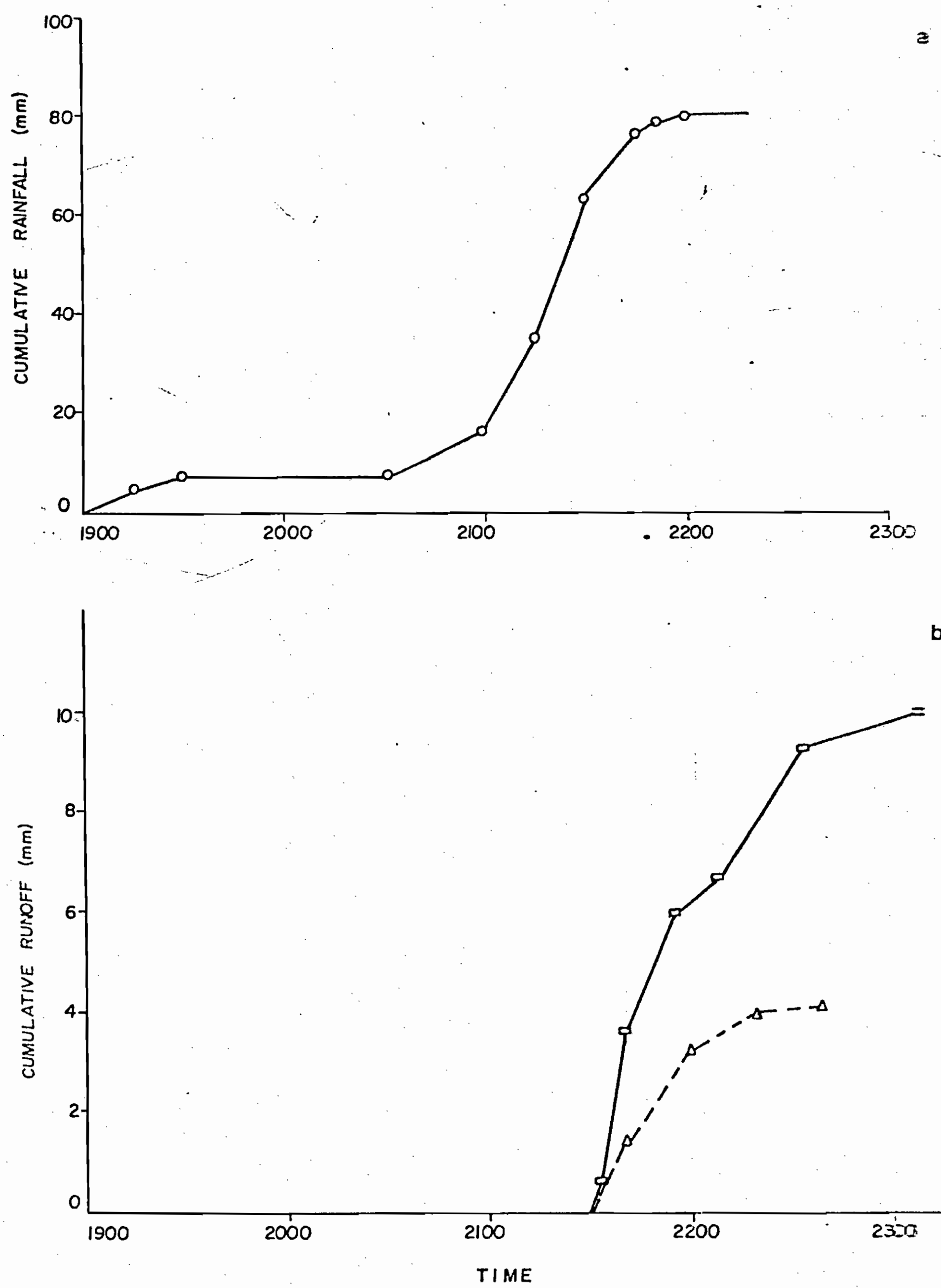

Fig. 9. Rainfall profile (a) and runoff hydrographs (b) from two catchments on Alfisols in southwestern Nigeria growing maize (□——□) and *Mucuna* (△——△) cover, for a storm on 28 August, 1982. Total runoff for the maize plot, 10.0 mm; total runoff for *Mucuna*, 4.0 mm.

Table XXI

Effects of No-Tillage and Plowed System on Runoff and Soil Erosion under Maize on Two Soils in Brazil[a]

				Conventional tillage		No-tillage	
Location	Soil	Slope (%)	Rainfall (mm)	Soil loss ($t\ ha^{-1}$)	Runoff (mm)	Soil loss ($t\ ha^{-1}$)	Runoff (cm)
Campinas	Latosol Roxa	6.3	1347	3.1	35.8	2.5	35.9
Pindorama	Podzol Lins	10.8	1139	40.9	143.7	13.4	95.8

[a] Modified from Benatti *et al.* (1977).

grown on 11, 22, and 52% slopes. Reduced tillage is recommended as a conservation measure for maize–soybean rotation in the mountainous regions of Ecuador (Portch and Hicks, 1980). Freebairn and Wockner (1982) reported data on runoff and soil movement under four tillage systems in Australia. The techniques leaving the greatest amount of crop residue intact were the most effective in reducing soil erosion. Along the wet tropical coast of Queensland in northeastern Australia, Capelin *et al.* (1983) observed drastic reductions in soil erosion with the no-till mulch system. Soil erosion was 10, 15, and 135 t ha^{-1} $year^{-1}$ on granitic red earth under no-till with mulch, no-till without mulch, and plowed treatments, respectively, and 25, 70, and 170 t ha^{-1} $year^{-1}$ on bleached yellow earth under no-till with mulch, mulch incorporated, and plowed treatments, respectively.

In Ghana, Baffoe-Bonnie and Quansah (1978) reported from their studies on Alfisols at Kumasi that reduced tillage caused the least compaction, maintained high porosity, and had the lowest soil and water losses (Table XXII). For similar soils and ecologies near Kumasi and Ejura, Bonsu and Obeng (1979) observed that no-tillage reduced runoff by 70 and 90% and soil erosion by 97 to 98% of that from conventionally plowed treatments. Field experiments conducted at IITA, Ibadan, Nigeria, on 4- to 5-ha agricultural catchments indicate that a no-tillage system can control runoff and erosion on slopes of up to 15% (Fig. 10, Table XXIII). With this system it is often unnecessary to use other erosion control measures, such as terraces and diversion channels, as long as there is an adequate quan-

Table XXII

The Effect of Different Tillage Practices on Runoff and Soil Erosion on an Alfisol near Kumasi, Ghana[a]

Tillage method	Soil erosion ($t\ ha^{-1}$)	Runoff[b] (cm)
Severe tillage	4.0	3.1
Medium tillage	0.9	0.8
Light tillage	0.2	0.3
Hand tillage	1.4	1.2
SE[c]	±0.2	±0.1
$LSD_{0.05}$[c]	0.6	0.4

[a] From Baffoe-Bonnie and Quansah (1978).
[b] Rainfall = 45.2 cm.
[c] SE, Standard error; $LSD_{0.05}$, least significant difference at 95% level.

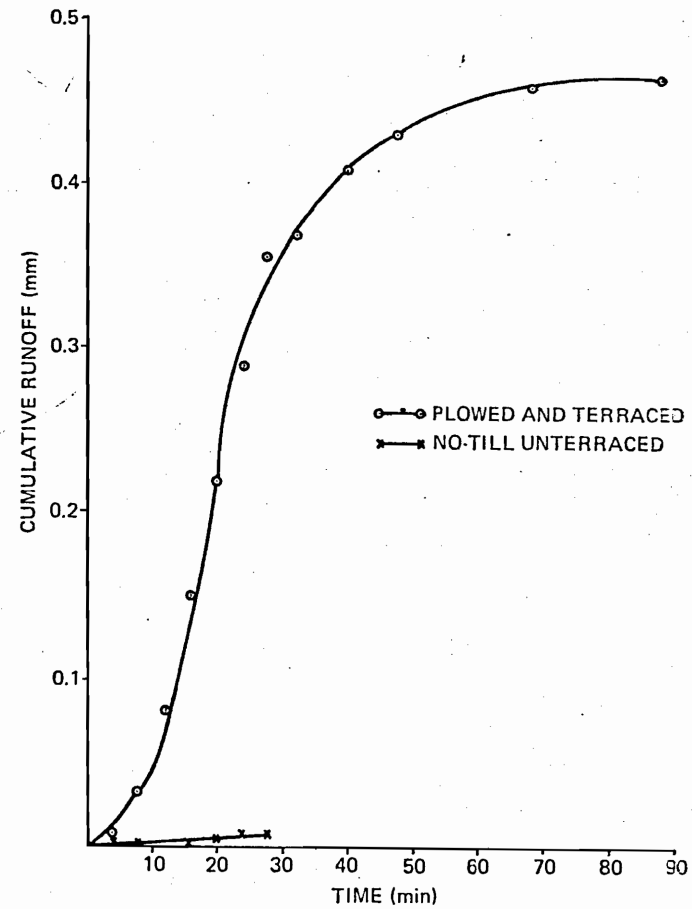

Fig. 10. Runoff hydrograph from two 5-ha catchments on Alfisols growing maize with no-till and conventionally plowed methods of seedbed preparation.

tity of crop residue mulch. The data in Fig. 11 on an Alfisol indicate that grain yields remain high in a no-till mulch system even after 24 consecutive crops of maize.

D. Crop Management

Soil loss from erosion is nearly proportional to the exposed soil surface (Hudson, 1976). For example, soil loss with 60% vegetative cover would be four times greater than that with 90% cover. Elwell and Stocking (1976)

Table XXIII

Runoff and Soil Erosion from Twin 5-ha Watersheds Growing Maize with No-Tillage and Plowing Methods of Seedbed Preparation[a]

Parameter	1979		1980	
	No-till	Plowed	No-till	Plowed
Rainfall (mm)	841		900	
Runoff (mm)	21.5	225.1	34.4	153.0
Soil erosion (t ha^{-1})	0.13	5.50	0.33	1.90

[a] From Lal (1984).

reported that, on arable grasslands, runoff and soil erosion decrease exponentially with increases in the percentage of vegetative cover (Fig. 12). Krantz *et al.* (1978) demonstrated that soil erosion from bare watersheds on Vertisols was more severe than from cropped watersheds. The impor-

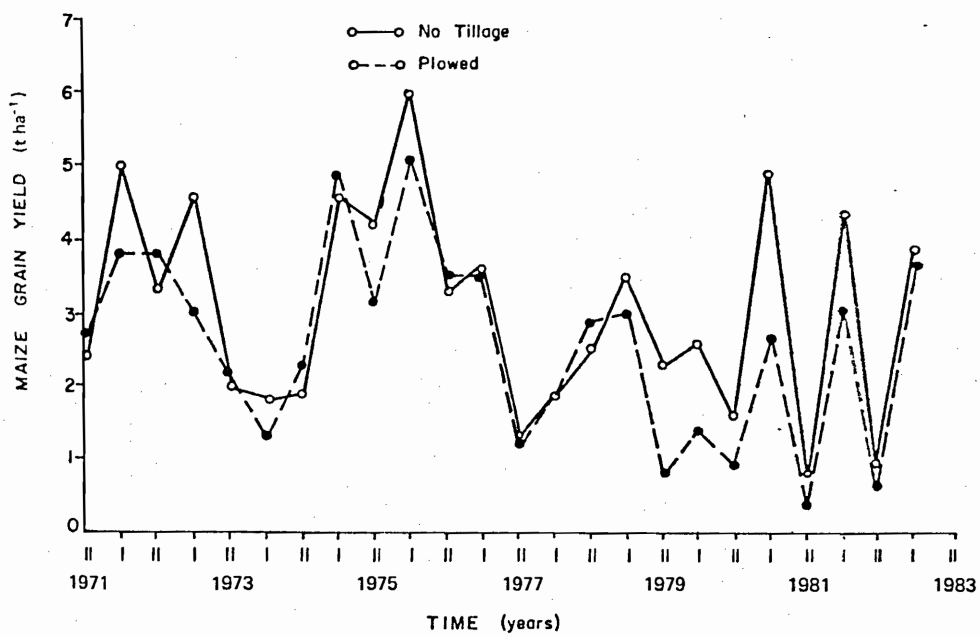

FIG. 11. Grain yields for 24 consecutive crops (two crops annually for 12 years) of maize grown with no-till and conventional plowing methods of seedbed preparation on an Alfisol in southwestern Nigeria. From Lal (1983a).

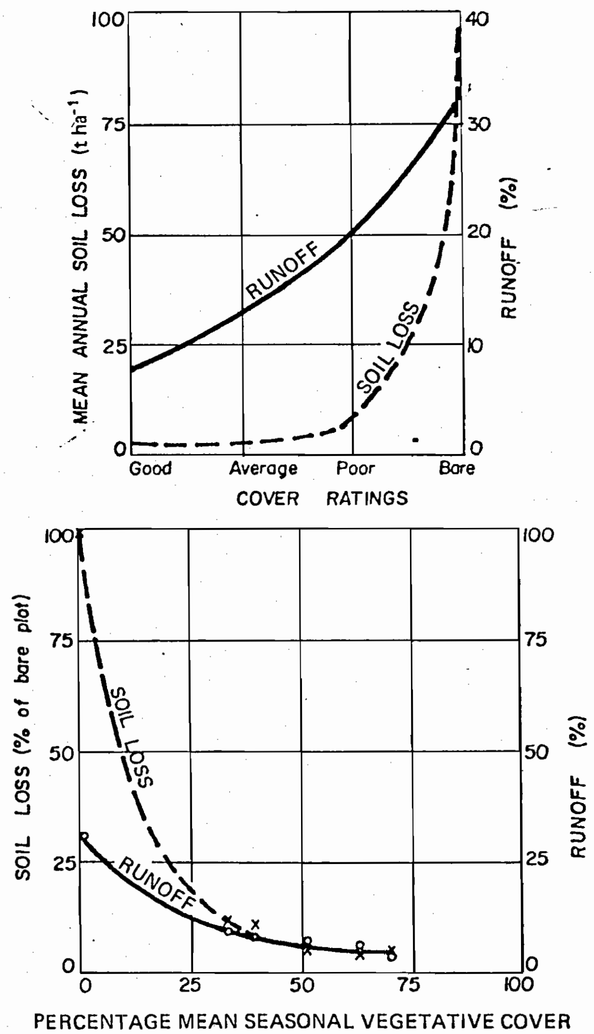

Fig. 12. Effects of percentage of vegetative cover on runoff and soil erosion. From Elwell and Stocking (1976).

tance of vegetative cover in controlling soil erosion was also demonstrated by Wilkinson (1975b) and Balek (1977).

Integrated crop management systems including contour planting, early sowing, balanced fertilizer application, and weed and pest control promote good crop growth and provide an early ground cover. The choice of an appropriate crop rotation and crop combination is equally important in soil conservation. Erosion is more severe in open-row crops such as

Soil Loss and Ru

Slope (%)	Cass
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5	8
10	12
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[a] From Aina *et al.*

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Table XXIV

Soil Loss and Runoff under Cassava Monoculture and Mixed Cropping of Cassava and Maize on an Alfisol near Ibadan, Nigeria[a]

Slope (%)	Soil loss ($t\ ha^{-1}\ year^{-1}$)		Runoff (%)	
	Cassava	Cassava and maize	Cassava	Cassava and maize
1	3	3	18	14
5	87	50	43	33
10	125	86	20	18
15	221	137	30	19

[a] From Aina *et al.* (1977).

maize and sorghum than in cowpea (Wilkinson, 1975b), and worse in rice than in cassava (Millington, 1982). Experiments conducted in India showed that contour farming and balanced fertilizer application reduced runoff by 5% and soil erosion by 75% (Bhatia and Chaudhary, 1977; Bhatia *et al.*, 1979). Hudson (1976) reported that soil loss under maize at a high level of production averaged about one-third the amount lost under maize at a medium level of production. Georges (1977) recommended early planting of sugarcane in Trinidad to provide ground cover during periods of intense rains.

The practice of mixed cropping—growing more than one crop in the same field simultaneously—is also an effective conservation measure. Cropping systems with multicanopy structure and those that provide continuous vegetative cover throughout the year protect the soil against raindrop impact and reduce runoff and soil erosion. Aina *et al.* (1977) observed that water runoff and soil erosion from a field of maize and cassava intercropped were significantly less than that from maize and cassava cropped separately (Table XXIV). Some crops, such as cassava and yam, require a long time to develop a canopy cover. Growing these crops in association with quick-growing and early-maturing crops should provide the additional ground cover neeeded to decrease erosion. Aina *et al.* (1979) reported that erosion decreases exponentially with increases in ground cover according to the following equation:[2]

$$Y = 5.4e^{-0.04X} \qquad (r = 0.63^*)$$

where Y is the soil loss in $t\ ha^{-1}\ cm^{-1}$ of rain, and X is the percentage of vegetative cover.

[2] *, Correlation coefficient significant at the 90% level.

E. Soil Conditioners

Synthetic soil conditioners are often recommended for improving soil aggregation stability under raindrop impact. They are generally too expensive, however, for small landholders in the tropics. Even so, chemical soil structure stabilizers can be useful for protecting industrial and urban areas during construction while vegetation is being established.

Alles (1971), using Curasol (polyvinyl acetate) as a chemical spray to control soil erosion in undulating terrain in Sri Lanka, observed a 30–50% reduction in soil erosion. Natural rubber formulations, which are cheaper than chemicals, have been found to be effective in improving soil structure and curtailing erosion on sandy soils in Malaysia (RRI, 1976; Soong, 1979). Because they improved soil physical properties, natural rubber emulsions decreased soil loss from 340 to 62 kg ha^{-1} (Soong, 1979). The data in Table XXV show that a combination of natural rubber and vegetative cover gave better erosion control than cover alone. Experiments conducted by Roose (1975) indicate that an application of Curasol reduced annual erosion by 40–75% and runoff by 25–55%. De Vleeschauwer *et al.* (1978) found that polyacrylamide also is useful in improving soil structure. However, the data in Table XXVI indicate that the crop residue mulch and no-till system control erosion as well as or more effectively than synthetic soil conditioners. Similar results have been reported for Kenya (Barber, 1979). Residue mulches and other organic materials are, in fact, the best conditioners for tropical soils.

XI. RUNOFF MANAGEMENT

Mechanical devices can be constructed to decrease runoff velocity and allow more time for water to seep into the soil. In some clayey soils with

Table XXV

Effect of Cover Crops and Rubber Emulsion Application on Stabilizing of Bunds in Malaysia[a]

Cover	Soil loss in 6 months (cm): With rubber emulsion	Soil loss in 6 months (cm): Without rubber emulsion
Control (no cover)	0.58	3.81
Pueraria	0.54	1.72
Pueraria + *Calopogonium*	0.26	0.58
Guatemala grass	0.23	1.22

[a] From RRI Malaysia (1976).

Table XXVI

Effect of Soil Conditioners and Crop Residue Mulch on Soil Erosion and Water Runoff from an Alfisol at Ibadan, Nigeria[a,b]

Treatment	Runoff		Soil erosion (t ha^{-1})
	mm	%	
Polyacrylamide	0.0	0.0	0.0
Bitumen	1.4	0.3	0.0
Soil penetrant	26.1	6.0	1.9
Mulch	0.0	0.0	0.0
No-till	0.0	0.0	0.0
Control	35.0	8.1	4.8

[a] From De Vleeschauwer *et al.* (1978).
[b] Rainfall = 433 mm.

steep slopes, land slides often occur if some provision is not made for safe disposal of excess runoff. An integrated approach toward management of the entire basin is the most desirable method to manage soil and water resources in the tropics (Madramootoo, 1982). A range of engineering devices is recommended for this purpose (Singh, 1974; Sheng, 1981). The usefulness of terraces in soil and water conservation is a controversial issue. Some researchers consider these devices to be effective tools of soil and water management, whereas others believe they do more harm than good. The effectiveness of these devices depends on soil, topography, and management, and it is rather difficult to generalize about their applicability.

A. Terraces and Diversion Banks

In the cane growing regions of Queensland, Australia, Veurman (1977) recommended the use of a top diversion bank to prevent runon and contour banks to break up a long slope and dispose of surplus runoff. He regarded a gradient of 8–10% as the maximum slope for contour layouts. In India, Gupta and Babu (1977) evaluated the efficiency of a range of engineering devices. Contour farming, channel terraces with contour farming, and channel terraces at 1.5 times the usual spacing reduced soil losses to 62, 47, and 25% and water losses to 57, 63, and 74%, respectively, of that occurring with up-and-down slope cultivation. Conservation bench terraces were also found to be extremely effective for rice cultivation on sloping lands (Bhushan, 1979). In Taiwan, bench terraces and broad-bottom hillside ditches are now widely used for steep land management (Liao and Chang, 1974, 1976, 1979, 1980; Chan, 1981a,b).

Hillside ditches and bench terraces should, however, be protected by planting *Paspalum* or another suitable cover crop. Wiersum (1980) also recommended terraces for controlling erosion in Java, Indonesia. In Cuba, Sagué Diaz *et al.* (1978) recommended terracing to control erosion in the Sierra del Rosario and have described techniques for construction and maintenance of terraces.

Many studies have indicated that terraces have no or only a slight effect on soil and water conservation. In Mexico, different types of terraces were evaluated by Ruiz Figueroa and Anaya Garduno (1980), with maize as a test crop. No significant differences were found in soil loss or grain and straw yield among broad-based terraces, level bench terraces, reverse bench terraces, Zingg conservation bench terraces, and sloping (1.6%) bench terraces. In the mountainous regions of Guatemala, Arledge (1980) observed that contour planting was usually adequate on heavy-textured soils with slopes of less than 6% and on coarse-textured sandy soils with slopes of as much as 12%. Bench terraces are, however, more effective on steeper slopes. In Kenya, Pereira *et al.* (1967) observed that terraces have no beneficial effects on water conservation up to a depth of 3 m under grazed pastures (Table XXVII). Thomas (1975) reported for Kenya that the use of conventional terraces sown with grass species does not control soil erosion. Because of unfavorable subsoil characteristics, Thomas *et al.* (1980) and Barber and Van Eijnsbergen (1981) recommend contour hedges for natural development of terrace systems on cultivated lands. Contour bunds, though widely used on clayey soils in India, are not an effective soil conservation measure (Gupta *et al.*, 1973) and often cause waterlogging and crop failure (Kampen *et al.*, 1981).

Table XXVII

Effect of Terraces on Soil Moisture Profiles beneath Grazed Pastures[a]

Terrace treatment	Depth (cm)	Duration (days) per year of water availability
Fields with 6-m vertical intervals between terraces	60	100
	120	75
	180	74
	240	77
	300	77
Fields with 1.5-m vertical intervals between terraces	60	107
	120	60
	180	75
	240	77
	300	77

[a] From Pereira *et al.* (1967).

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Table XXVIII

Runoff and Soil Loss from Terraced and Unterraced Catchments at Ibadan, Nigeria from a Single Rainstorm Received on 6 July, 1981[a]

Catchment	Runoff (mm)	Soil erosion (t ha^{-1})
Terraced	18.1	0.7
Unterraced	18.8	2.3

[a] From Lal (1983d).

If terraces are not properly constructed and adequately maintained, erosion can be more severe than without them (Greenland and Lal, 1977). Water runoff and soil erosion can be significantly reduced with adequately designed and properly constructed and maintained engineering systems. The data in Table XXVIII obtained from catchment studies at Ibadan, Nigeria, also indicate that, although graded channel terraces did not decrease water runoff, they did reduce runoff velocity and soil loss drastically. In Sierra Leone, Millington (1982) recommended stone and stick bunds constructed with native materials. Although soil losses with bench terraces were lower, the labor and construction cost were prohibitive (Table XXIX). Wall (1981) also recommended the use of straw barriers to curtail erosion on steep lands in El Salvador. Bench terraces, though effective on slopes up to 25°, are five times more expensive than hillside ditches and are not justified for low-value subsistence crops. These terraces are difficult to construct and require considerable technical supervision. Another serious disadvantage of terracing is that it requires a dramatic departure from the existing agricultural practices of subsistence

Table XXIX

Comparison of Soil Erosion Losses from Various Conservation Techniques in Sierra Leone[a]

	Soil loss (t ha^{-1})	
Terraces	Rice	Cassava
Bench terraces	7.5	—
Stone bunding	29.5	4.4
Stick bunding	27.3	27.3
Contour bunding	18.0	16.8
No conservation	40.7–54.5	11.2–55.1

[a] From Millington (1982).

upland farmers. Terraces are prohibitively expensive in some developing agricultural areas (Couper *et al.*, 1979) and can occupy as much as 35% of the cropping area on 10 to 12% slopes (Pereira *et al.*, 1967).

There is an almost negligible amount of data from the tropics on slope length management and its effect on runoff rate and erosion. In many regions terraces are recommended in spite of the deficiency of this research information on their design and construction. The widespread failure of these devices is, therefore, not surprising. Buffer strips of grass or herbaceous vegetation may be more effective and economical than terraces for controlling erosion and reducing runoff velocity (Table XXX, Roose, 1977a,b). Placing deep-rooted perennial shrubs at regular intervals may provide the barrier needed to decrease runoff velocity and encourage sedimentation. "Alley cropping" of grain crops with tree legumes has also shown promise (Kang *et al.*, 1981; Wilson and Lal, 1982). Experiments conducted at IITA show that properly established hedges of these leguminous shrubs at adequate spacing can be just as effective in decreasing runoff and erosion from plowed strips as the no-till system with crop residue mulch. However, 2 to 3 years are required to establish hedges of perennial shrubs. Residue mulching and organic farming seem to be the most practical approaches for soil and water conservation in the tropics.

B. Contour Ridges

Seedbed preparation with the ridge–furrow system allows more time for infiltration of water into the soil. Two adjacent ridges are sometimes tied together to develop a series of small basins that permit rainwater to infiltrate the soil where the rain falls. This system of water conservation

Table XXX

Effect of Mulch Tillage and Strip Cropping on Runoff and Soil Erosion for Three Soils in Puerto Rico[a]

	Typic Tropuhumult		Vertic Eutropepts		Typic Dystropepts	
Treatment	Erosion ($t\ ha^{-1}$)	Runoff (cm)	Erosion ($t\ ha^{-1}$)	Runoff (mm)	Erosion ($t\ ha^{-1}$)	Runoff (mm)
Conventional tillage	12.8	9.6	2.0	15.6	18.7	5.1
Mulch tillage	1.2	11.2	1.3	15.0	0.6	2.9
Grass strip	4.0	11.8	1.9	14.8	0.8	3.2
Sod cover	0.7	10.9	—	—	—	—

[a] From Barnett *et al.* (1972).

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and erosion control can be effective for soils with relatively stable structure and for gentle slopes of up to about 7%. On structurally unstable soils, ridges often collapse during heavy rainstorms and cause severe erosion.

In Kenya, Pereira *et al.* (1967) observed that tied ridges reduced soil loss from 3 to 1 t. On sloping lands in India, Panwar and Singh (1976) observed that castor planted in contour trenches produced high yields because of favorable soil moisture storage in the root zone. Bonde and Patel (1978) observed in trials along river banks in Gujrat, India, that transplanting tobacco seedlings on ridges reduced runoff by 46%, soil loss by 38%, and nitrogen loss by 51%, compared with transplanting on the flat. Krantz (1981) and Kampen *et al.* (1981) recommended a graded ridge–furrow system for soil and water conservation on Vertisols in the semiarid tropics of India. Their data (Table XXXI) show that a graded-ridge–furrow system permits less runoff and soil erosion than fallowed plots, even during the monsoon.

If the ridges are made up and down the slope, as they are in West Africa, runoff and soil erosion are generally more from ridged land than from flat land. Kowal (1972a,b) observed on loess soils in northern Nigeria that the least erosion occurred on nonridged land, irrespective of the treatment cover. Terraces with ridges at about 1-m intervals lost five times more soil than flat land did. The greatest loss was from broad lands with alternate tied ridges. Collinet and Valentin (1979) reported that on loess soils in northern Ivory Coast the effects of furrowing and tied ridges are short-lived. Haq (1983) reported from southern Sudan that ridges made up and down the slope do more harm than good.

XII. RESEARCH AND DEVELOPMENT PRIORITIES

Impressive progress has been made in gaining an understanding of erosion processes and in discovering effective soil conservation techniques for a wide range of ecologies throughout the tropics. Some extremely useful information is also available about techniques of new land development and management of forest resources in the humid and subhumid tropics. Nevertheless, there is still not enough original research information from properly designed and adequately equipped field-scale projects conducted in tropical regions for a long enough period that the results are meaningful. More than 75% of the data reported on erosivity and erodibility is mere repetition of ideas developed in temperate regions and shows a

Table XXXI

Rainfall, Runoff, and Soil Loss Measured at Outlets for Two Watersheds[a]

	BW1[b]				BW4C[c]			
Year	Rainfall (mm)	Runoff (mm)	Peak runoff rate (m^3 sec^{-1} ha^{-1})	Soil loss (t ha^{-1})	Rainfall (mm)	Runoff (mm)	Peak runoff rate (m^3 sec^{-1} ha^{-1})	Soil loss (t ha^{-1})
1973	697.0	51.2	0.03	3.0	734.6	58.7	0.06	3.9
1974	810.4	116.1	0.20	1.3	806.9	223.4	0.22	6.8
1975	1041.6	162.2	0.06	0.7	1055.0	253.2	0.15	2.1
1976	687.3	73.1	0.09	0.8	710.1	238.1	0.16	9.2
1977	585.6	1.5	0.01	0.1	585.9	53.0	0.06	9.2
1978	1125.2	272.5	0.11	3.4	1116.7	410.1	0.15	9.7

[a] After Kampen *et al.* (1981).
[b] BW1, Cropped deep Vertisol watershed.
[c] BW4C, Rainy season fallow deep Vertisol watershed.

complete disregard for standardizing methodologies or identifying the specific soil, climatic, and topographic parameters that aggravate soil erosion in the tropics. Researchers in the tropics need to be more original in studying the basic processes of soil erosion and in developing techniques for soil conservation that are technically viable and socially acceptable to small landholders in the tropics. It is equally important that techniques already known to be effective in combating soil erosion be put into practice immediately.

Erosion research, capital intensive and time consuming as it is, requires innovation, drive, and perseverance. The topics of this research must be adequately outlined and sharply focused, and earnest effort must be made to bring this basic research to bear on practical problems. In view of the present state of research information for the tropics, basic data collection must have first priority. The existing models, although useful for identifying knowledge gaps and defining researchable topics, are no substitute for good, solid field data.

1. Erosion rates. There is considerable talk about the severity of erosion in the tropics. Yet, little is known about the rate of erosion in the diverse and heterogeneous soils and moisture regimes of this region. What is the relationship, if any, between sediment load in tropical rivers and the physiographic–geomorphological conditions and land uses of tropical watersheds? What is the delivery ratio for sediment discharge from major ecological zones?

2. Erosivity. Basic research information is needed on rainfall factors such as drop size distribution, energy load, effect of wind-driven rain and interaction between rainfall and antecedent soil moisture content. These factors should be related to routinely measured parameters such as rainfall amount and intensity. Relationships between soil–sand splash and energy parameters for major rainfall regimes should also be developed. This information is available only for three or four locations in the tropics.

3. Erodibility. If soil erosion is as severe in the tropics as we think it is, what makes tropical soils so extremely vulnerable to erosion? To answer this question we need to understand the dynamic aspects of soil structure and its interaction with the hydrothermal regime and of soil management for different land uses. What soil parameters influence soil erodibility? The role of organic matter content, iron and aluminum oxides, and particle size distribution (including lack of silt fraction and predominance of gravels and concretionary materials) should be assessed for a wide range of soils. Why do tropical soils get easily compacted and crusted? Little is known about soil-water interaction under mechanized upland agriculture.

4. Steep land management. The little research information available indicates some controversy about the effects of slope length, gradient, and aspect on runoff and erosion in tropical soils. Data from adequately designed field experiments showing these effects for a range of slope gradients and types of surface soil management are very scarce indeed. This information is a prerequisite for appropriately designed terrace and engineering systems for runoff management.

5. Soil erosion–productivity relationships. Assessment of the impact of soil erosion on crop productivity is necessary for conservation and development planning. To what extent can the loss of topsoil be compensated for by inputs such as fertilizer and manure? How is the tolerable limit of soil loss related to the rate of new soil formation? These questions should be explored for a wide range of soils, crops, and ecologies in the tropics.

6. Soil degradation. It is important to establish a numerical or quantitative criterion for assessing erosion-induced soil degradation. The effects of erosion should, therefore, be related to measurable soil quality parameters such as available water holding capacity and effective rooting depth.

7. Conservation-effective farming systems. A review of the available literature indicates the importance of ground cover by mulch, cover crops, no-till, vegetative cover, and mixed cropping in erosion control. These measures should be validated and adapted for different soils, crops, and ecologies and should be integrated into local farming systems. Local research of this type should receive high priority.

8. Methodology. In order for results to be compared and easily adapted from one region to another, it is important that methodology be standardized.

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