Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). IAHS Publ. no. 133.

Analyses of different processes governing soil erosion by water in the tropics

R. LAL
International Institute of Tropical Agriculture,
Oyo Road, PMP 5320 Ibadan, Nigeria

ABSTRACT Soil erosion hazard in tropical Africa is a serious threat towards sustained productivity. The available basic research information on soil, climate, and land use is rather sketchy and indicates that the severity of the erosion hazard may be attributed to soil characteristics, low soil loss tolerance, and climatic factors that lead to accelerated soil erosion following a change in land use. Researchers in the tropics have yet to establish appropriate methods for monitoring and estimating, precisely and by simple techniques, soil erodibility and erosivity in relation to soil and rainfall characteristics. There is a little information on the soil loss tolerance or acceptable levels of soil loss.

Analyse de différents processus qui sont à l'origine de l'érosion du sol par l'eau sous les tropiques

RESUME L'éventualité d'érosion du sol en Afrique tropicale est une sérieuse menace pour une production soutenue. Les renseignements disponibles provenant des recherches de base sur les caractéristiques des sols, le climat et l'utilisation du sol sont plutôt vagues et ils indiquent que la sévérité de l'érosion éventuelle peut être attribuée aux caractéristiques des sols, à la faible tolérance de ces sols en ce qui concernent les pertes et aux facteurs climatiques lesquels conduisent à une érosion accélérée après modification de l'utilisation du sol. Les chercheurs sous les tropiques ont encore à établir une méthodologie approprié pour suivre et estimer avec précision et par des techniques simples l'érodibilité du sol et l'érosivité en relation avec les caractéristiques des sols et de la pluie. Il y a peu d'informations sur la tolérance des pertes des sols et le seuil acceptable de pertes en sol.

INTRODUCTION

Soil erosion, a complex phenomenon as it is, begins with detachment of soil aggregates by impacting raindrops. Translocation of the detached soil particles may be caused by raindrop impact as splash, through gravitational force downslopes as creep, or by overland flow. The latter plays the most dominant role in sediment and solute transport. The relative importance of the different factors that affect soil erosion from arable lands has been widely investigated, and many empirical relations have been developed to predict the erosion hazard using parametric methods that involve a range of these variables (Musgrave, 1947; Gottschalk & Brune, 1950; Wischmeier *et al.*, 1958; Hudson, 1961; Farnham *et al.*, 1966). Factors included in these parametric equations are indices of climate, soil, landscape or topography, and management. This report describes the processes of soil erosion in tropical Africa and reviews their relative importance, methods of determination, and research priorities. The examples of research data from experiments conducted at the International Institute of Tropical Agriculture (IITA) in southwest Nigeria are reviewed to compare results obtained elsewhere in the tropics.

SOIL ERODIBILITY

Susceptibility of a soil to erosion as a dynamic property is a time dependent function and its magnitude varies with soil characteristics:

$$K(t) = f\ (\text{structure, texture, organic matter, amorphous Fe and Al oxides}) \qquad (1)$$

$$\frac{dK}{dt} = f\ (\text{soil and crop management and land use}) \qquad (2)$$

where K is soil erodibility and t is time.

Soil erodibility is a composite factor and comprises "detachability" and "transportability". Whereas detachability depends on soil and rainfall characteristics, overland flow, with or without rill systems and their characteristics, governs transportability.

Soil detachment and transport

Soil splash, defined as spattering of small soil particles by impacting raindrops (Mazurak & Mosher, 1968, 1970), is caused by the disruptive forces acting against the bonding energy of the cementing agents. Consequently, soils with a weak or a single-grain structure consisting mainly of primary soil separates are more easily splashed than soils with well developed structure because the aggregates require some energy to be detached prior to being splashed. Yariv (1976) investigated the mechanism of soil detachment by rainfall, and visualized the phenomenon to take place in three stages. In the first stage, when soil is still dry, detachment results from collision of elastic bodies. In the second stage, the soil is fluidized and the impacting raindrops cause the splash of the fluidized soil. In the third stage, the fluidized soil is covered by an overland flow that, combined with the impacting raindrops, causes the detachment of soil aggregates. Impacting raindrops in the overland flow increase turbulence and enhance soil detachment (Ghadiri & Payne, 1977, 1979). In the first and second stages, the hydration energy can play a significant role in soil detachment especially for soils containing predominantly expanding lattice clay minerals, e.g. vertisols. The hydration energy or heat of wetting is a function of soil moisture potential or the antecedent soil moisture content: the higher the heat of wetting (more negative the soil-water

Table 1 Effect of soil moisture potential and heat of wetting on detachability of a vertisol (Bruce-Okine & Lal, 1975)

pF	Number of impacting raindrops* required at different water temperatures (°C)		
	30	40	50
4.4	194	173	143
7.0	21	19	11

*Drop diameter 6.7 mm with a terminal velocity of 50 cm s^{-1}.

potential), the more the soil detachment (Table 1).

The relative effect of overland flow on soil detachment, as it occurs in the third stage, may be smaller than raindrop impact and depends on the soil and flow characteristics. Young & Wiersma (1973) observed that reducing the raindrop impact energy by 89% decreased soil loss by over 90% indicating that soil detachment was primarily caused by the impacting raindrops. Depending on the soil and topographical characteristics, the soil detachment from a rill system by overland flow can also be significant (Mosley, 1974).

Measurement and estimation of soil erodibility

Soil erodibility is the combined effect of the soil's infiltration capacity and the soil's resistance to particle detachment and transport. A numerical index of soil erodibility (K), as defined in the universal soil loss equation (USLE), can be measured directly in the field by establishing a "unit plot" or can be estimated using simulated rainfall or simply from soil properties.

Factors affecting soil erodibility Those soil parameters that affect soil structure, slaking, and water transmission characteristics also affect soil erodibility. However, the factors that affect soil detachability may not be necessarily the same as those that affect transportability. For a majority of soils in the tropics and elsewhere, it may be difficult to associate any single factor with soil erodibility. Bennett (1926) observed for some soils in the humid tropics of Central America that the relative concentration of Al and Fe oxides had a significant effect on soil erodibility. The nature of the colloid complex as measured by the plasticity index (Rose, 1960), particle size distribution, and soil organic matter content (quantity and quality) also have a significant effect on soil erodibility. The nature of cations on the exchange complex and their interaction with the soil organic matter content play a significant role in soil erodibility (El-Swaify *et al.*, 1970). Kandiah (1976) observed that organic matter content improved resistance to erosion only in soils with a low sodium absorption ratio (SAR). Structural stability of soils with high SAR was not drastically improved by the increase in soil organic matter content. The biomass or the biologically active soil organic matter and the microbial by-products also have an important effect on structure and soil erosion susceptibility.

Based on these soil properties, a range of indices that are indirectly related to soil erodibility have been developed. Many researchers have observed the percentage of water stable aggregates to be a good index of soil erodibility (Yamamoto *et al.*, 1973). In francophone West Africa, various researchers have compared stability of aggregates to wet sieving after pretreatment with organic liquids, e.g. alcohol and benzene (Henin *et al.*, 1958). The amount of colloidal fraction, in dispersed or aggregated state, has also been widely used (Combeau & Monnier, 1961). However, more often, it is observed that the field behaviour of a soil in regard to water erosion is not related to any one index but to a number of indices. For some soils in Nigeria, it was observed that organic matter content, pF ratio, and cation exchange capacity (CEC) were related to soil erodibility (De Vleeschauwer *et al.*, 1978). The choice of a suitable index, therefore, depends on various factors including the ability of an index to predict the field behaviour of soil in terms of its reaction to splash erosion under natural rainstorms. Data in Table 2 indicate that when organic matter is included with soil properties, the correlation with water stable aggregates is higher than with soil loss by erosion (0.51 *vs.* 0.30 and 0.40 *vs.* 0.92). However, when cation exchange capacity, a measure of clay activity, is used, the correlation is higher with soil loss. Measurements of water stable aggregates *per se* were not as good predictors of resistance to erosion as the exchange capacity and organic matter.

Measurements with rainfall simulator One of the factors that complicates the direct relation between laboratory measured indices and field behaviour is the antecedent soil moisture content. Other factors remaining the same, soil erosion caused by a rainstorm is significantly influenced by the soil moisture content. In addition, the magnitude and the nature of overland

Table 2 Effects of laboratory determined indices on soil erodibility as indicated by the multiple correlation coefficient (R^2) of soil loss with indices of soil erodibility (De Vleeschauwer *et al.*, 1978)

Soil parameters	Multiple correlation coefficient (R^2)		
	Soil loss	LD	WS
% clay + pF ratio	0.19	0.15	0.25
% clay + % organic matter	0.09	0.32	0.21
% clay + CEC	0.40	0.25	0.07
% clay + aggregation	0.13	0.14	0.09
pF ratio + CEC	0.43	0.17	0.25
% organic matter + CEC	0.83**	0.78**	0.47
% organic matter + % aggregation	0.29	0.36	0.40
CEC + % aggregate	0.39	0.15	0.09

LD = Instability index of De Leenheer & De Boodt (1959).
WS = % stable aggregates > 200 μ by sieving in water.
CEC = Cation exchange capacity.

** *Statistically significant at $P = 0.01$.*

Table 3 Comparative evaluation of soil erodibility indices based on different indices and micro-plot ratings (Aina *et al.*, 1981)

Soil	Wet sieving index	Raindrop impact		Laboratory micro-plot	
		Index	Rating	Index	Rating
Oxic Paleustalf	0.72	0.009	Very stable	0.001	Very stable
Typic Ustrothent	6.53	0.125	Highly erodible	0.66	Highly erodible
Oxic Paleustalf	3.50	0.083	Highly erodible	0.66	Highly erodible
Oxic Paleustalf	2.89	0.077	Moderately erodible	0.35	Moderately erodible
Orthoxic Tropohumult	0.55	0.009	Very stable	0.001	Very stable
Oxic Paleustalf	1.21	0.027	Stable	0.001	Very stable
Typic Chromulstert	1.80	0.007	Very stable	0.94	Highly erodible
Typic Paleudult	4.60	0.063	Moderately erodible	0.34	Moderately erodible

flow and the network of rill system that develops only under field conditions are also important factors. In spite of the discrepancies in the results obtained, a qualitative relationship between the laboratory measurements and field behaviour can be established (Table 3). A quantitative measure of soil erodibility as determined from micro-plots in laboratory conditions may not be identical to that obtained on the field plots because the infiltration characteristics of a shallow layer of soil are not similar to that of a deep profile.

Estimation from soil properties Wischmeier *et al.* (1971) developed an erodibility nomograph for estimating erodibility from soil properties. Application of this nomograph has not yet been widely evaluated for soils in the tropics and may be questionable for vertisols, andisols, and soils with high gravel contents in the surface horizon. Experiments conducted at IITA indicated that erodibility measurements made by the field rainfall simulator were generally higher than those obtained with natural rainfall, but those estimated by this nomograph were equivalent to the direct measurements reported elsewhere (Lal, 1976) (Table 4). Application of this nomograph for estimating erodibility of soils may be improved by considering those properties that are important in determining structural stability of soils in the tropics, e.g. content of Fe and Al oxides etc.

Table 4 Comparison of the estimated erodibility (K) by a nomograph with that measured by a field rainfall simulator (Mondjalis *et al.*, 1981)

Nomograph	Rainfall simulator	Nomograph	Rainfall simulator
0.04	0.10	0.06	0.13
0.10	0.31	0.10	0.07
0.08	0.04	0.09	0.16
0.06	0.02	0.10	0.08
0.04	0.05		
0.04	0.23	Mean 0.06	0.12

RAINFALL EROSIVITY

The aggressivity of a rainfall or the driving force that causes soil detachment has been related to different rainfall characteristics. Since soil erosion is a work function and the source of energy to perform this work is the rainfall, it is appropriate to relate soil erosion to the energy load of a rainstorm or to any indirect measure that is related to its energy load.

Momentum

Momentum, a product of mass and velocity, has been empirically related to soil detachment and found by many researchers to be directly related to the amount of soil detached. Rose (1960) observed that the mass of soil detached per unit area was more closely related to the momentum than to the kinetic energy of a rainfall. Rose argued that momentum is a measure of the pressure exerted by rainfall on a soil. Pressure or the force per unit area has the nature of a mechanical stress and is, therefore, related to the breakdown of aggregates.

The momentum concept has also been supported by the work of Williams (1969) who observed a logarithmic relationship between momentum and rainfall intensity as described in equation (3).

$$\log \text{momentum (dynes cm}^{-2}\text{ h}^{-1}) = 0.711\,18 \log (I) - 1.461 \qquad (3)$$

On the contrary, Kinnell (1973) reported a linear relationship between momentum and rainfall intensity:

$$\text{momentum (dynes cm}^{-2}\text{ s}^{-1}) = 0.0213\,(I) - 0.62 \qquad (4)$$

where I is the rainfall intensity in mm h^{-1}. Under the conditions at Ibadan, Nigeria, momentum was found to be linearly related to rainfall amount and intensity as described in equations (5) and (6):

$$\text{momentum (J m}^{-2}\text{ s}^{-1}) = 6.67\,P + 9.32 \qquad r = 0.81^{**} \qquad (5)$$

$$\text{momentum (J m}^{-2}\text{ s}^{-1}) = 4.79\,I_{30} + 8.74 \qquad r = 0.75^{**} \qquad (6)$$

where P is the rainfall amount (mm) and I_{30} is the maximum 30 min intensity (mm h^{-1}). These experiments indicated that the median drop size was not related to the momentum of a rainstorm.

Kinetic energy

Many researchers believe that the kinetic energy of a rainfall is a more important factor in soil splash and in initiating erosion phenomenon than the momentum. Kinetic energy of a rainstorm may be related to drop size distribution and rainfall intensity. In general, tropical rains have higher energy loads than temperate rains (Lal, 1979, 1980). For example, Kowal & Kassam (1976) reported much higher values (34.6 J m^{-2} mm^{-1}) of energy load than those reported from subtropical (Elwell & Stocking, 1975) and temperate regions.

The energy load of a rainstorm has been related to easily monitored parameters, e.g. rainfall amount and intensity.

** *Statistically significant at* $P = 0.01$.

Kinnell (1973) related the kinetic energy to rainfall rate as described in equations (7) and (8):

$$\text{KE (ergs cm}^{-2}\text{ s}^{-1}) = 8.37\ I - 45.9 \qquad (7)$$

$$\text{KE (ergs cm}^{-4}\text{ s}^{-1}) = 1269\ I + 1041 \qquad (8)$$

where I is the intensity ranges between 0 and 300 mm h^{-1}.

Kowal & Kassam (1976) related the kinetic energy of a rainfall to the rainfall amount per storm as shown by

$$\text{KE} = (41.4\ R_a - 120.0) \times 10^3 \text{ ergs cm}^{-1} \qquad r = 0.99 \qquad (9)$$

where R_a is the amount of rainfall per storm (mm).

Elwell (1979) related kinetic energy to rainfall amount for southern Africa with a linear relationship:

$$\text{KE} = 18.846\ P \qquad (10)$$

where KE is in J m^{-2} and P is the mean rainfall amount (mm).

Sand splash monitored with Ellison's splash cups was found to be equally related to kinetic energy or momentum for rainfalls received in Ibadan, Nigeria (Lal, 1980). Kinetic energy was related to rainfall amount and rainfall intensity according to the equations below:

$$\text{KE} = 24.50\ P + 27.6 \qquad r = 0.81^{**} \qquad (11)$$

$$\text{KE} = 18.18\ I_{30} + 18.18 \qquad r = 0.71^{*} \qquad (12)$$

where KE is in J m^{-2}, P is amount of rainfall (mm) and I_{30} is the 30 min maximum intensity. Median drop size was not related to kinetic energy.

Drop size distribution

The energy load of a rainstorm can be influenced by the drop size distribution, which, in turn, can be related to rainfall charateristics. 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 under a natural rainfall. The cumulative drop size of a storm and intensity calculated over different time intervals may not be necessarily related. Measurements made at IITA, Ibadan, indicated that no correlation existed between the median drop size and intensity calculated for different time intervals. The values of the correlation coefficient were 0.057, 0.058, and 0.047 for the maximum intensity monitored for 7.5, 15, and 30 min, respectively. Surprisingly, the median drop size was also found to be unrelated to sand splash (r = 0.05).

Some data obtained on drop size distribution of tropical rainstorms have indicated that D_{50} of above 2.5 mm is quite common (Lal, 1979). An example of the data on drop size distribution of rainstorms measured at Ibadan shown in Fig. 1 indicates that most erosive rains had a D_{50} ranging between 1.70 and 2.55 mm.

* *Statistically significant at P = 0.05.*
** *Statistically significant at P = 0.01.*

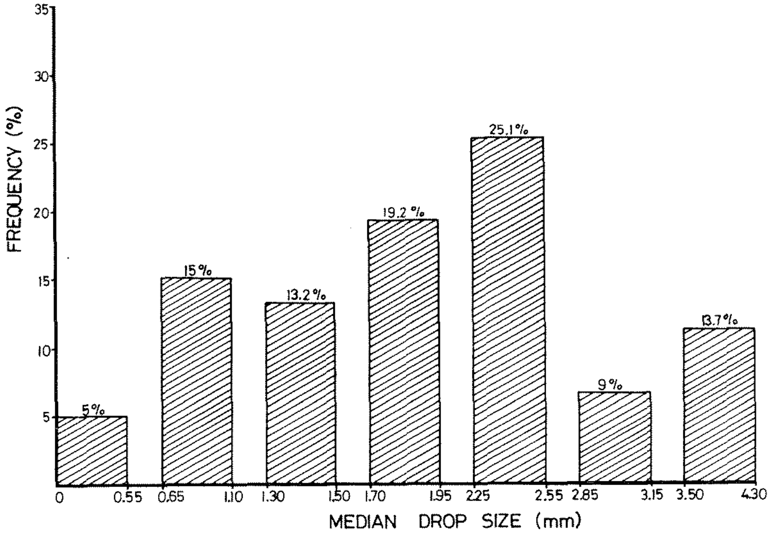

Fig. 1 Drop size distribution of rain storms in Ibadan from 1977 to 1979.

Rainfall rate vs. rainfall amount

Rainfall rate and amount can be more easily and routinely measured than kinetic energy, momentum, and drop size distribution. Consequently, many researchers feel that rainfall amount may be the most practical parameter for predicting a soil erosion hazard (Elwell & Stocking, 1975).

Rose (1961) and Mazurak & Mosher (1968, 1970) observed that detachment of particles is linearly related to rainfall intensity although the relationship is different for soils of different structural stability. Furthermore, the structural breakdown may be considerably more sensitive to rate than to duration or amount (Rose, 1960).

Sand splash measured for rainstorms in Ibadan indicated good linear relationships, with rainfall amount and intensity measured at different times (equations (13) and (14)):

$$S = 17.6\ I_{30} + 1.64 \qquad r = 0.84^{**} \tag{13}$$

$$S = 22.7\ P + 19.73 \qquad r = 0.84^{**} \tag{14}$$

where S is the sand splash (g m^{-2}), I_{30} is the 30 min maximum intensity (mm h^{-1}) and P is the rainfall amount (mm h^{-1}). Both kinetic energy and momentum were also related to sand splash, although, the correlation coefficient of sand splash with kinetic energy or momentum was no more than with rainfall amount or intensity. Therefore, the rainfall amount and intensity can be equally good and more practical predictors of the soil erosion hazard than the energy parameters.

Estimation of erosivity

Various empirical relations have been developed over the past 20

** *Statistically significant at* $P = 0.01$.

years to estimate climatic erosivity from easily and routinely measured rainfall parameters. Some of the important indices used include EI_{30} (Wischmeier *et al.*, 1958), KE>1 (Hudson, 1971) AI_m (Lal, 1976), and p^2/P (Fournier & Henin, 1959). Many researchers have attempted to modify these parameters by other factors considered to be important in soil detachment. For example, antecedent soil moisture content has been judged to be an important factor by many. The importance of wind in increasing rainfall erosivity has also been recognized (Lal, 1976; Aina *et al.*, 1976; Lal *et al.*, 1978).

SLOPE FACTOR

Under natural field conditions, a change in slope steepness also results in alteration of the soil characteristics that influence runoff and erosion. If the soil characteristics remain the same, increase in slope steepness results in an increase in runoff velocity, and, therefore, the carrying capacity of sediments. The effect of slope gradient on soil and water loss depends on soil type and its physico-chemical properties. The effect of slope steepness also depends on the nature of the slope rather than on mean or the average slope (Lal, 1976; Foster & Wischmeier, 1974).

The effect of slope length on runoff and erosion is rather ambiguous. Long slopes may produce more total runoff and soil erosion, however, the runoff and soil erosion per unit area may not necessarily be more from long slopes and may, in fact, be less (Lal, 1976). The time of concentration is generally more on long slopes, thus, allowing more time for water infiltration. The effect of slope length on runoff and soil loss for a range of slope steepness is shown in Table 5. It is apparent from the data that long slope lengths have less runoff and soil loss than short lengths.

SOIL LOSS TOLERANCE

Soil loss tolerance is defined as the maximum rate of soil

Table 5 Effect of slope length and gradient on runoff (mm) and erosion (t ha^{-1} $year^{-1}$) from an alfisol in western Nigeria measured in 1978

	Slope length (m)							
	5		10		15		20	
Slope (%)	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion
1	188	5	245	3	188	7	96	2
5	579	143	289	95	232	127	166	52
10	508	219	303	230	190	236	160	164
15	403	191	266	212	206	289	165	306

erosion that will permit sustained crop productivity, economically, and indefinitely. Soil loss tolerance limits, commonly used in deciding suitable soil and crop management practices, range from 2.5 to 12.5 t ha^{-1} $year^{-1}$ depending on soil characteristics. Soil erosion is serious if the land productivity cannot be restored even by introducing improved systems of management. The profile characteristics, such as distribution of organic matter and plant nutrients, are important in deciding the soil loss tolerance.

The soil loss tolerance for shallow tropical soils with a limited rooting depth is extremely low. This is due to the fact that the loss of nutrient rich surface soil cannot be compensated by the addition of fertilizers alone (Figs 2 and 3). Decline in crop yield on eroded plots is associated with deterioration of both soil physical and nutritional characteristics. Since the enrichment ratio of eroded sediments is 3 to 5 for nutrient elements such as organic matter, nitrogen, phosphorus and exchangeable bases, soil fertility can rapidly decline with accelerated soil erosion.

Studies reported earlier (Lal, 1980) indicated that soil erosion under maize-cowpea crop rotation with conventional methods of seedbed preparation can be of the order of 1, 10, 10 and 40 t ha^{-1} $year^{-1}$ for 1, 5, 10 and 15% slopes, respectively. These values of soil loss should be corrected for the enrichment ratio factor of about 4. The equivalent soil loss under maize-cowpea rotation with conventional tillage system will be of the order of 4, 40, 40 and 160 t ha^{-1} $year^{-1}$. At this rate of soil loss, maize yield from some shallow soils can decline at the rate of 320, 400, and 1600 kg ha^{-1} $year^{-1}$ (Lal, 1980). If the mean maize grain yield, at the recommended rate of NPK application is 4 t ha^{-1}, maize yield will be halved within 6 years of continuous cultivation on gentle slopes and within 2-3 years on steep slopes. Most of this decline is irreversible for shallow rooted crops.

The rate of soil loss tolerance for these soils should be such as to sustain crop yield without resorting to lengthy bush fallow rotation or expensive remedial measures. The experience for alfisols in western Nigeria indicates that a soil loss of 0.1-0.5 t ha^{-1} $year^{-1}$ may cause a 50% yield reduction in about 50-100 years. The currently used rate of 12.5 t ha^{-1} $year^{-1}$ is certainly too high for many shallow soils in tropical Africa.

MONITORING SOIL EROSION PROCESSES ON LARGE BASINS AND LAND DEVELOPMENT SCHEMES

Large scale land development schemes in Africa and elsewhere in the tropics have necessitated mass deforestation by means that result in drastic degradation of soil properties and lead to accelerated soil erosion. Mechanical means of deforestation using heavy power machinery are inevitable because labour is expensive and not readily available. Heavy power machinery results in soil compaction, decreases water infiltration rate, and enhances runoff and erosion. There are few properly designed experiments in tropical Africa to investigate fluvial processes under different

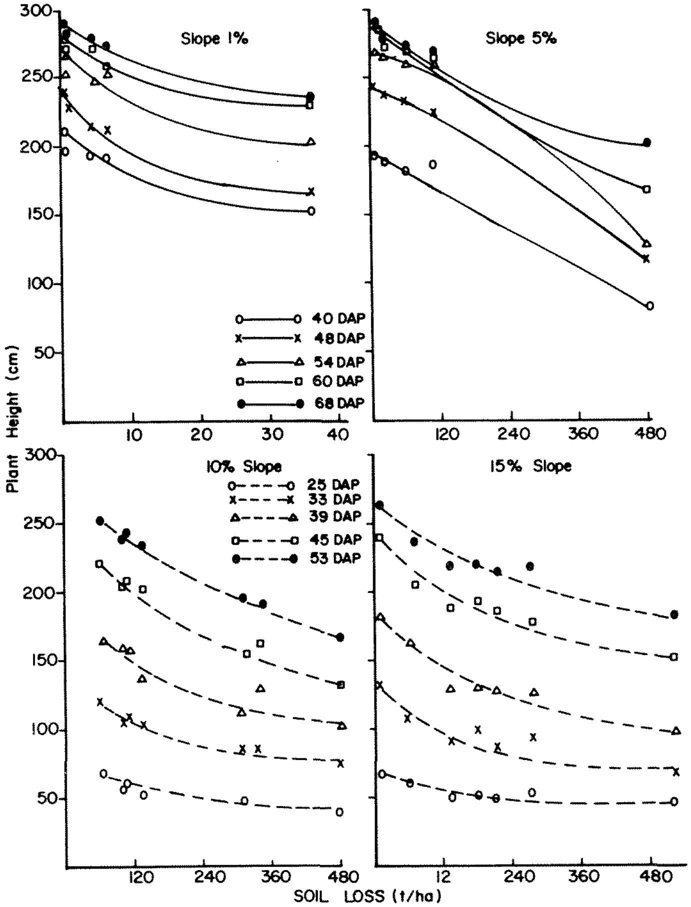

Fig. 2 Effect of the magnitude of soil erosion on plant vigour.

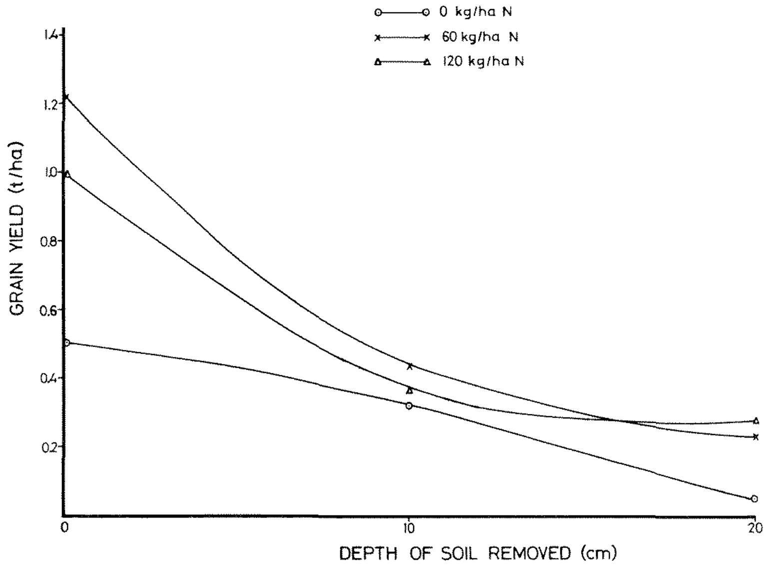

Fig. 3 Effect of depth of soil loss on maize grain yield for different levels of N.

land use systems. This type of basic research information is necessary for planning land development and designing appropriate research techniques to monitor precisely hydrological characteristics of agricultural catchments including runoff, seepage losses, water yield, evapotranspiration, soil water storage, and movements of solids and solubles in runoff and seepage water. Design of appropriate flumes and weirs and runoff sampling devices is critical for obtaining this basic information. This is a basic prerequisite for development of appropriate land use systems in the tropics that may lead to sustained productivity economically and indefinitely.

REFERENCES

Aina, P. O., Lal, R. & Taylor, G. S. (1976) Soil and crop management in relation to soil erosion in the rainforest of western Nigeria. In: *Soil Erosion: Prediction and Control,* 75-84. SCSA Special Publ. 21.

Aina, P. O., Lal, R. & Taylor, G. S. (1981) Relative susceptibility of some Nigerian soils to water erosion. *Ife J. Agric.* (in press).

Bennett, H. H. (1926) Some comparisons of the properties of humid tropical and humid-temperate American soils; with special reference to indicated relations between chemical composition and physical properties. *Soil Sci.* 21, 349-375.

Bruce-Okine, E. & Lal, R. (1975) Soil erodibility as determined by raindrop technique. *Soil Sci.* 119, 149-157.

Combeau, A. & Monnier, G. (1961) A method for the study of structural stability - application to tropical soil. *African Soil* 6, 33-52.

De Leenheer, L. & De Boodt, M. (1959) Determination of aggregate stability by the change in mean weight-diameter. *Meded. Landb. Gent* 24, 290-351.

De Vleeschauwer, D., Lal, R. & De Boodt, M. (1978) Comparison of detachability indices in relation to soil erodibility for some important Nigerian soils. *Pédologie* XXVIII, 5-20.

El-Swaify, S. A., Ahmad, S. & Swindlae, L. D. (1970) Effect of absorbed cations on physical properties of tropical red and tropical black earths. *J. Soil Sci.* 21, 188-197.

Elwell, H. A. (1979) Destructive potential of Zimbabwe Rhodesia rainfall. *Zimbabwe Rhodesia Agric. J.* 76 (6), 227-232.

Elwell, H. A. & Stocking, M. A. (1975) Parameters for estimating annual runoff and soil loss from agricultural lands in Rhodesia. *Wat. Resour. Res.* 11 (4), 601-605.

Farnham, C. W., Beer, C. E. & Heinemann, H. G. (1966) Evaluation of factors affecting reservoir sediment deposition. In: *Symposium of Garda* (October 1966, Hydrology of Lakes and Reservoirs), 747-758. IAHS Publ. no. 71.

Foster, G. R. & Wischmeier, W. H. (1974) Evaluating irregular slopes for soil loss prediction. *Trans. Am. Soc. Agric. Engrs* 17, 305-309.

Fournier, F. & Henin, S. (1959) A new climatic formula for evaluating the specific degradation of soil. *C. R. Acad. Sci.,* *Paris* 248, 1694-1969.

Ghadiri, H. & Payne, D. (1977) Raindrop impact stress and the breakdown of soil crumbs. *J. Soil Sci.* 28, 247-258.

Ghadiri, H. & Payne, D. (1979) Raindrop impact and soil splash. In: *Soil Physical Properties and Crop Production in the Tropics* (ed. by R. Lal & D. J. Greenland), 95-103. Wiley, Chichester, UK.

Gottschalk, L. C. & Brune, G. M. (1950) Sediment design criteria for the Missouri basin loess soils. *USDA Soil Conserv. Service Tech. Publ. no. 97.*

Henin, S., Monnier, G. & Combeau, A. (1958) Méthode pour l'étude de la stabilité structural des sols. *Ann. Agron.* 9, 73-92.

Hudson, N. W. (1961) An introduction to the mechanics of soil erosion under conditions of subtropical rainfall. *Rhodesian Sci. Ass. and Trans.* XLIX, 14-25.

Hudson, N. W. (1971) *Soil Conservation.* B. T. Batsford, London.

Kandiah, A. (1976) Influence of organic matter on the erodibility of a saturated illitic soil. *Mededelingen van de Faculteit Landbouwwetenschappen, Rijksuniversiteit Gent* 41 (1), 397-406.

Kinnell, P. I. A. (1973) The problem of assessing the erosive power of rainfall from meteorological observations. *Soil Sci. Soc. Am. Proc.* 37 (4), 617-621.

Kowal, J. M. & Kassam, A. H. (1976) Energy and instantaneous intensity of rainstorms at Samaru, northern Nigeria. *Trop. Agric.* 53 (3), 185-198.

Lal, R. (1976) Soil erosion problems on an alfisol in western Nigeria and their control. *IITA Monograph* 1.

Lal, R. (1979) Conservation - effective farming systems in the humid tropics. In: *Soil Erosion and Conservation in the Tropics* (Proc. ASA Symp., Fort Collins, Colorado, USA, 5-10 August 1979).

Lal, R. (1980) Soil conservation: preventive and control measures. *Conservation 80*, Nat. College Agric. Engng, Silsoe, UK, 21-25 July 1980.

Lal, R., Lawson, T. L. & Anastase, A. H. (1978) Erosivity of tropical rains. Conference Proceeding. In: *Assessment of Erosion in USA and Europe* (Proc. Conf. Ghent, Belgium, 27 Feb-3 March 1978).

Mazurak, A. P. & Mosher, P. N. (1968) Detachment of soil particles in simulated rainfall. *Soil Sci. Soc. Am. Proc.* 32, 716-719.

Mazurak, A. P. & Mosher, P. N. (1970) Detachment of soil aggregate by simulated rainfall. *Soil Sci. Soc. Am. Proc.* 34, 798-800.

Mondjalis, P., Lal, R., Babalola, O. & Sengele Ndani (1981) Estimating erodibility of some soils in Zaire by a nomogram. *J. of the Faculty of Agriculture of the Nat. Univ. of Zaire* (in press).

Mosley, M. P. (1974) Experimental study of rill erosion. *Trans. Am. Soc. Agric. Engrs* 17 (5), 909-913, 916.

Musgrave, C. W. (1947) Quantitative evaluation of factors in water erosion, a first approximation. *J. Soil Wat. Conserv.* 2 (3), 133-138.

Rose, C. W. (1960) Soil detachment caused by rainfall. *Soil Sci.*

89, 28-35.

Rose, C. W. (1961) Rainfall and soil structure. *Soil Sci*. 91, 49-54.

Stocking, M. A. (1977) Rainfall energy in erosion: some problems and applications. *Research Discussion Paper, Department of Geography, University of Edinburgh* (1977) vol. 13.

Stocking, M. A. & Elwell, H. A. (1976) Rainfall erosivity over Rhodesia. *Trans. Inst. Brit. Geogr.* 1 (2), 231-245.

Williams, M. A. (1969) Prediction of rainfall splash erosion in the seasonally wet tropics. *Nature* 222, 763-765.

Wischmeier, W. H., Johnson, C. B. & Cross, B. V. (1971) A soil erodibility nomograph for farmland and construction sites. *J. Soil Wat. Conserv.* 26 (5), 189-192.

Wischmeier, W. H., Smith, D. D. & Uhand, R. E. (1958) Evaluation of factors in the Soil Loss Equation. *Agric. Engng* 39 (8), 458.

Yamamoto, T. & Anderson, H. W. (1973) Splash erosion related to soil erodibility indexes and other forest soil properties in Hawaii. *Wat. Resour. Res.* 9 (2), 336-345.

Yariv, S. (1976) Comments on the mechanism of soil detachment by rainfall. *Geoderma* 15 (5), 393-399.

Young, R. A. & Wiersma, J. L. (1973) The role of rainfall impact in soil detachment and transport. *Wat. Resour. Res.* 9 (6), 1629-1636.