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Effects of slope length and terracing on runoff and erosion on a tropical soil

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ABSTRACT Runoff and soil erosion measurements were made for 5, 10, 12.5, 15, 20 and 37.5 m slope lengths on tropical soils of 10 and 15% slopes in western Nigeria. Comparisons were also made for runoff and erosion from terraced and unterraced basins of 3-4 ha in size and managed with the conventional and no-tillage systems. Runoff per unit area was more from short than long slopes and decreased at the rate of 6 mm $m^{-1} year^{-1}$. On the contrary, the soil erosion increased linearly with the increase in slope length at the rate of 2.4 t $ha^{-1} m^{-1}$ for slope lengths between 5 and 20 m. The sediment load per unit runoff also increased with the increase in slope length at the rate of 25 kg $mm^{-1} m^{-1}$. Terracing decreased erosion and water runoff on ploughed basins, and was not necessary on untilled basins. The no-till system with crop residue mulch is an effective erosion preventive measure.

INTRODUCTION

Soils of the humid and subhumid tropics can be intensively used, and have potential to increase the food production substantially. Their productive potential can be realized if the rapid rate of soil degradation and accelerated erosion are effectively brought under control. The technology to control and reverse these degradation processes is available, although adaptive research is still needed to evaluate and adapt these soil conservation techniques for a range of soils and agroecological regions. According to some estimates, only 11 and 22% of the cultivable land area is being used for food crop production in tropical South America and Africa, respectively (Hoppers, 1976). However, the ever-increasing demand for food production for those regions has necessitated an annual rate of new land development of about 6-10 million ha (Boerma, 1975). If the forest is removed properly and the subsequent soil management systems are adopted to ensure erosion control, soil productivity can be sustained. If not, accelerated soil erosion and a very rapid rate of decline in soil organic matter content set the degradation processes in motion and may eventually lead to irreversible soil degradation. Restoration of severely eroded and degraded lands, if at all possible, may require lengthy fallow periods that may take as much as 50 years (Low, 1955).

The objective of this report is to evaluate the effects of slope length on runoff and erosion. These results are discussed in terms of the effectiveness of graded channel terraces for erosion control on arable lands in the tropics. The results presented are from field experiments conducted at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. These results may be applicable elsewhere for similar soils, climate, and cropping systems.

EFFECTS OF SLOPE LENGTH ON RUNOFF AND EROSION

The rate and quantity of water runoff per unit area are affected more by the rainfall intensity and soil hydrologic properties than by slope length. The slope length may, therefore, have either a negligible or even a negative effect on water runoff per unit area (Wischmeier & Smith, 1978). The less runoff per unit area from long slopes is attributed to the longer time of concentration and to increased surface detention in comparison with short slopes. However, if the soil is not protected by a vegetative cover and its dense root mass, the concentrated water runoff from long slopes causes more soil loss than from short slopes. Consequently, the soil loss per unit area increases with an increase in slope length (Zingg, 1949; Wischmeier, 1972). This increase in soil loss from long as compared to short slope lengths is proportional to about the 0.6 power of the slope length. The numerical value of the exponent ranges from 0.3 to 0.7 depending on soil properties, rainfall characteristics, and farming systems adopted (Wischmeier & Smith, 1978).

The effects of 5, 10, 12.5, 15, 20, and 37.5 m slope lengths on runoff and erosion from bare and ploughed soil were evaluated at IITA for 10 and 15% slopes. The water runoff and soil loss for all rainstorm events in 1977 were monitored by the collection system described elsewhere (Lal, 1976).

Data in Table 1 indicate that runoff per unit area was generally more from short than from long slopes. The mean runoff decreased linearly with the increase in slope length at the rate of about 6 mm $m^{-1}year^{-1}$ (Fig.1(a)). On the contrary, the soil erosion increased with the increase in slope length up to 20 m, and then decreased for the 37.5 m length (Table 2). This decrease in erosion for the 37.5 m length was probably due to an irregular slope that caused sediment deposition prior to the point of measurement. The soil loss increased linearly between the 5 and 20 m slope lengths at the rate of about 2.4 t $ha^{-1}m^{-1}$ (Fig.1(b)).

The soil loss:runoff ratio, an index of the sediment

TABLE 1 The effect of slope length on water runoff (mm $year^{-1}$)

Slope steepness (%)	*Slope length (m):* 5	10	12.5	15	20	37.5
10	310.6	187.8	220.7	166.9	243.1	121.5
15	207.0	253.8	226.2	226.2	85.8	93.9
Mean	258.8	220.8	223.5	196.6	164.5	107.7

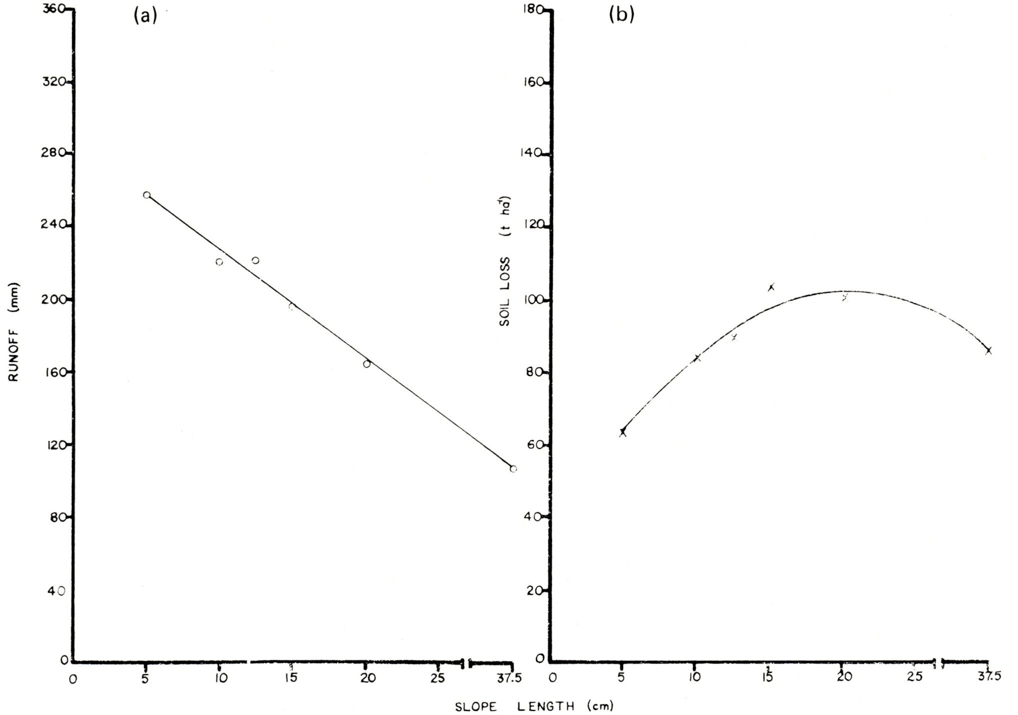

FIG.1 The effect of slope length on (a) runoff and (b) erosion per unit area.

transportability of water runoff, also increased with the increase in slope length (Fig.2). This implies that the concentrated water runoff on long slopes has greater particle detachment and transport capacity than the runoff originating from short slopes. Between the slope lengths of 5 and 20 m, the sediment load in water runoff increased linearly at the rate of about 25 kg $mm^{-1}m^{-1}$

Regression equations relating total runoff and soil erosion from all rainfall events in 1977 to slope length are shown in Table 3. The soil loss per unit runoff increased exponentially with the increase in slope length. The length exponent and the coefficients were different for the two slope steepnesses investigated, probably because of the differences in soil properties. The relationship between soil loss per unit of rainfall and slope length also fitted

TABLE 2 The effect of slope length on soil erosion (t ha^{-1})

Slope steepness (%)	*Slope length (m): 5*	*10*	*12.5*	*15*	*20*	*37.5*
10	*82.1*	*101.9*	*134.9*	*107.1*	*74.5*	*118.6*
15	*52.6*	*72.8*	*44.6*	*100.4*	*126.8*	*52.5*
Mean	*67.4*	*87.4*	*89.8*	*103.8*	*100.7*	*85.6*

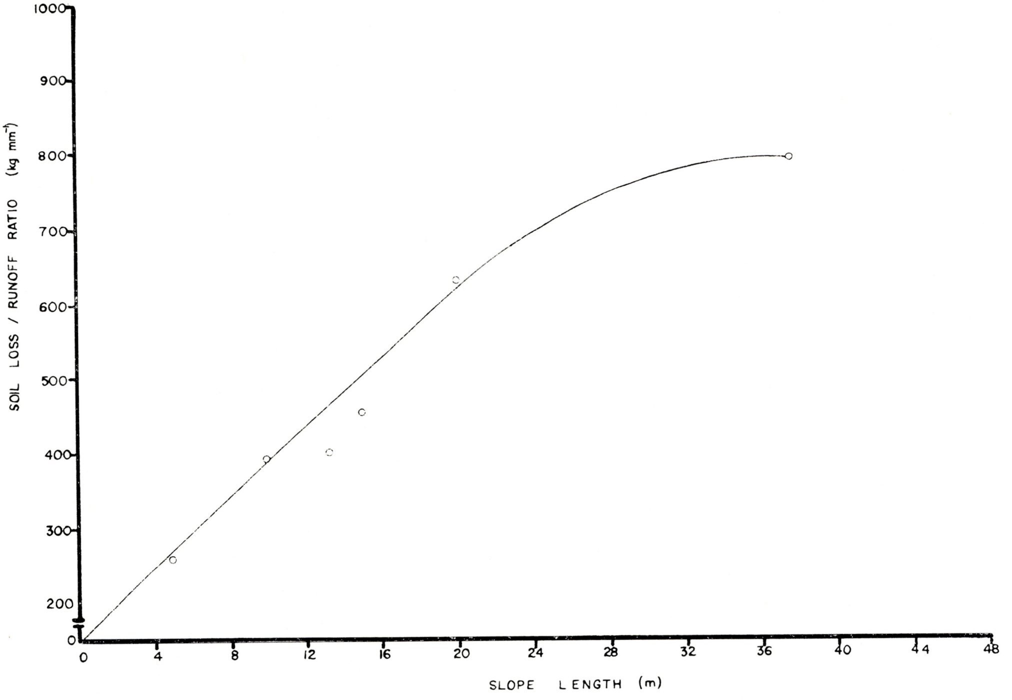

FIG.2 The effect of slope length on the soil loss:runoff ratio.

an exponential model. However, the length exponent was small and ranged between 0.02 and 0.06. Runoff per unit area decreased with the increase in slope length and this decrease in runoff was

TABLE 3 Regression models relating slope length to runoff and erosion

Parameter	*Slope (%)*	*Regression equation*	*Correlation coefficient*
Soil loss (t ha^{-1} mm rainfall^{-1})	10	$A = 0.132\ L^{-0.02}$	$r = 0.975$
Soil loss (t ha^{-1} mm rainfall^{-1})	15	$A = 0.074\ L^{0.058}$	$r = 0.977$
Soil loss (t ha^{-1} mm runoff^{-1}	10	$A = 0.00007\ L^{3.23}$	$r = 0.999$
Soil loss (t ha^{-1} mm runoff^{-1}	15	$A = 0.091\ L^{0.93}$	$r = 0.991$
Runoff (mm)	10	$W = 17.22\ L^{-0.33}$	$r = 0.969$
Runoff (mm)	15	$W = 13.99\ L^{-0.35}$	$r = 0.969$
Runoff:rainfall ratio	10	$W = 0.59\ L^{-0.29}$	$r = 0.970$
Runoff:rainfall ratio	15	$W = 0.50\ L^{-0.32}$	$r = 0.969$

A = erosion, W = water runoff, L = slope length (m).

proportional to about the -0.3 power of slope length (Table 3).

TERRACING AND EROSION CONTROL

Graded channel terraces are expensive to construct and maintain (Couper *et al.*, 1979). Depending on slope steepness and soil properties, about 10-20% of land is occupied by terraces, grassed waterways, and diversion channels. Furthermore, the effectiveness of terraces in reducing erosion to an acceptable level is questionable at its best and devastating at its worst (Greenland & Lal, 1977). Breaks in terraces due to improper construction and poor maintenance generally lead to severe gully erosion (Fig.3).

FIG.3 Breaks in improperly constructed terraces can cause severe gullying.

Basic information regarding the effect of slope length on runoff and erosion is needed for designing an appropriate terrace system. If the vertical interval between terraces is small and the inter-terrace slope length is short, more land goes out of production and mechanized farm operations are difficult to conduct. On the other hand, large vertical intervals and long inter-terrace slope lengths increase the risk of accelerated soil erosion. These basic rules are further complicated by the soil and crop management and the method of seedbed preparation.

TERRACING AND EROSION CONTROL ON CONVENTIONAL PLOUGHED BASINS

The effectiveness of terracing for erosion control was evaluated in two basins each of about 4 ha. The slope steepness was about 8% and the length was about 300 m. These basins were surveyed for 1 m contours and graded contour banks were constructed on one basin at a

FIG.4 H-Flume with a water level recorder (white box) and a Coshocton sampler.

vertical interval calculated by the following formula:

$$\text{Vertical interval (cm)} = 10.2\,X + 30.5 \qquad (1)$$

where X = slope (%). The mean inter-terrace slope length was about 15 m. Both basins were managed according to conventional tillage, involving ploughing and harrowing. Runoff measurements were made by an H-Flume and a water level recorder (Fig.4).

Data in Table 4 compare three separate rainstorm events in respect of the effects of terracing on runoff and erosion. With adequate spacing and regular maintenance, terraces were extremely effective in decreasing water runoff and soil erosion measured at the flume. The mean measured runoff and erosion on the unterraced basin was 2.78 and 15.38 times more than on the terraced basin under a similar cropping system and with similar methods of seedbed preparation. However, the actual runoff and erosion from the terraced basin was substantially more than could be measured because of water detention and sediment deposition in the channels and

TABLE 4 Runoff and erosion from terraced and unterraced basins under maize grown with conventional tillage methods (data for first season, 1981)

Period	Runoff (mm):		Erosion (kg ha^{-1}):	
	Terraced	Unterraced	Terraced	Unterraced
May	0.13	17.34	0.32	880.3
June	0.23	6.01	0.53	172.8
July	15.51	20.68	264.30	2229.9
Total	15.87	44.03	265.15	3283.0

FIG.5 Sediment deposition in the channel.

waterways (Fig.5). The "delivery ratio" for the terraced basin may be only 20-30% for sediment and 50-60% for water runoff. Terraces are therefore more effective in decreasing the quantity of sediment that reaches a stream or a drainage system than in decreasing soil detachment and transport from the inter-terrace region.

The soil loss:water runoff ratio was 16.71 and 74.56 kg mm^{-1} for the terraced and unterraced watersheds, respectively. This differential sediment load implies that the sediment detachment and transport capacity of water runoff for the unterraced basin was about 4.5 times greater than for the terraced basin.

TERRACE/TILLAGE INTERACTION

Recent studies in the tropics (Lal, 1976) and elsewhere (Harrold & Dragoun, 1969) have shown that the no-tillage system with a crop residue mulch is an effective erosion prevention measure. The residue mulch protects the soil against raindrop impact, and the lack of soil crust development under the mulch maintains a favourable infiltration rate that prevents runoff and erosion. With this effective soil conservation system, terraces are not required. For example, the data in Table 5 compare the runoff and soil loss from a conventionally tilled and terraced basin with that from a no-till and unterraced basin under maize cowpea rotation. The runoff and erosion from the tilled/terraced basin was 27.1 and 49.1 times more than from the no-till/unterraced basin. The no-tillage system was more effective in preventing runoff and soil erosion than the graded channel terraces. Furthermore, the no-till system reduced soil erosion even more effectively than it reduced the water runoff. For example, the soil loss:water runoff ratios were 2.25 and 4.08 kg mm^{-1} for no-till/unterraced and ploughed/terraced

TABLE 5 Effects of tillage systems and terracing on runoff and soil loss (data for the first and the second season, 1981)

Period	Runoff (mm): No-till/ unterraced	Tilled/ terraced	Erosion (kg ha^{-1}): No-till/ unterraced	Tilled/ terraced
June	0.01	13.13	0.03	64.80
July	0.67	4.65	1.55	4.37
October	0.04	1.71	0.04	10.40
Total	0.72	19.49	1.62	79.57

basins, respectively. This means that the soil detachment and transport capacity of runoff from the tilled/terraced basin was twice that from the untilled/unterraced basin.

GENERAL DISCUSSION AND CONCLUSIONS

The data presented indicate that for regular slopes the runoff per unit area is generally more from short than long slopes. On the contrary, the soil loss per unit runoff or the soil loss per unit area increases with increasing slope length. The mathematical relationship between slope length and runoff or soil erosion depends on soil properties, slope characteristics, and the farming system. These factors also determine the optimum slope length or the inter-terrace width for effective erosion control.

Properly constructed and well maintained terraces reduce water runoff and soil erosion from ploughed lands. Terraces are effective more in reducing the sediment that reaches the drainage system than in minimizing the inter-terrace erosion by splash and soil detachment caused by impacting raindrops. The no-tillage system with a crop residue mulch is an effective erosion prevention measure, and reduces soil erosion and water runoff more than terraces on a ploughed watershed. Furthermore, the effectiveness of terraces in decreasing soil loss depends on their regular maintenance.

Farmers in the tropics may be reluctant to adopt these mechanical erosion control measures because they involve heavy capital investment and their effectiveness is questionable. In comparison, biological measures and no-till systems are more effective and involve less capital investment (Roose, 1977). This is not to say that the no-till system is applicable for all soils and crops in the tropics. In spite of this, there is tremendous scope for adapting these biological measures for a wide range of soils and agro-ecological environments. The new land development schemes planned for the humid and subhumid tropics should be implemented with adaptation of those systems of management that are based on erosion prevention rather than on control measures.

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