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Effects of slope length, slope gradient, tillage methods and cropping systems on runoff and soil erosion on a tropical Alfisol: preliminary results

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Abstract Field runoff plots of variable slope lengths and 4 m width were established on a tropical Alfisol of about 7 to 9% slope at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. There were six slope lengths varying from 10 to 60 m with 10 m increment. An additional plot of 25 m length was established to study the soil erodibility factor *K*. There were two tillage methods e.g. ploughed and no-till system of seedbed preparation. Corn (*Zea mays*) was sown in the first season and cowpea (*Vigna unguiculata*) in the second season. Runoff and erosion were significantly influenced by tillage methods and slope length. For ploughed plots, slope length had a negligible effect on runoff per unit area. In contrast, however, erosion from ploughed plots increased as a power function of slope length and slope length parameters. In no-till treatments, both runoff and soil erosion decreased linearly or inversely with increase in slope length. This differential response due to tillage methods may be attributed to the variable effects of slope length, crop residue mulch, and tillage methods on time of concentration and runoff velocity.

Effets de la longueur de la pente, de son gradient, des méthodes de labour, des systèmes de culture sur l'écoulement et l'érosion du sol dans le cas d'un Alfisol tropical: résultats préliminaires

Résumé Des parcelles de ruissellement présentant des longueurs de pente variables de 4 m de largeur ont été installées sur un Alfisol tropical avec une pente de 7 à 9% environ à l'Institut International d'Agriculture Tropicale (IITA), Ibadan, Nigéria. Il y avait six parcelles inclinées dont la longueur variait de 10 à 60 m avec 10 m d'espacement. Une parcelle additionnelle de 25 m de longueur était installée pour étudier le facteur *K* d'érodibilité des sols. Deux méthodes de labour: labour conventionnel et absence de labour ont été utilisées. Le maïs (*Zea mays*) était planté en première saison et le vigna (*vigna unguiculata*) en deuxième saison. Le ruissellement et l'érosion sont significativement influencés par les méthodes de labour et la longueur de pente. Pour les parcelles labourées, la longueur de pente a un effet négligeable sur le ruissellement par unité de surface. Cependant, l'érosion sur les parcelles labourées augmente comme une fonction de la longueur de la pente et les paramètres de la longueur de la pente. Dans les parcelles non-labourées, ruissellement et érosion diminuent d'une façon linéaire ou inversement avec l'augmentation de la longueur de la pente. Cette réponse différentielle dûe aux méthodes de labour peut-être attribuée aux influences variables de la longueur de pente, des débris de culture et des méthodes de labour sur le temps de concentration et la vitesse de ruissellement.

INTRODUCTION

Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins or the runoff water enters a well-defined channel that may be part of a drainage network or a constructed channel (Smith & Wischmeier, 1957).

Upland or rill-interrill erosion is a two-phase process involving detachment and transport of soil particles. Detachment depends on: (a) combined kinetic energy of raindrop, overland flow, and the interaction between raindrop and overland flow, (b) resistance of the soil to the shearing forces listed above, (c) and the resistance or protective effects of crop residue mulch and of the canopy cover. The shearing effects of overland flow are related to its velocity and depth. The velocity of overland flow depends on slope gradient, its depth, and the time of concentration. The latter is a function of slope length. The time of concentration increases with increase in slope length. Consequently, the time available for overland flow to infiltrate into the soil is more on longer than on shorter slope lengths.

Effects of slope length on water runoff and erosion are not adequately understood. There are few field experiments conducted specifically to quantify the effects of slope length on runoff and erosion. Controlled laboratory experiments are difficult to conduct for slope lengths that represent field situations. Rainfall simulators can only be used to relatively small slope lengths. Under field conditions effects of slope length on runoff and erosion are confounded by the interacting effects of slope gradient, slope aspect, slope shape, and the changes in soil physical and hydrological properties along the hillslope due to differences in soil forming factors. Furthermore, slope parameters and soil properties are not independent. Whereas the effects of slope length (L) and gradient (S) can be assessed through a combined LS factor (Wischmeier *et al.*, 1958), those of slope shape and alterations in slope-induced soil properties are difficult to account for in a mathematical model.

Despite the paucity of verifiable research data relating slope length to erosion, there are some commonly used mathematical functions for estimating runoff and soil erosion from plots of variable slope lengths and gradients (Tacconi *et al.*, 1982; Van Liew & Saxton, 1983; De Ploey, 1984; Bergsma, 1985; Gilley *et al.*, 1985; Poesen, 1985; Schroeder, 1987). Some of these functions, however, require validation and adaption in relation to soil properties, tillage methods, and management practices.

Effects of slope length on runoff

Effects of slope length on runoff per unit area are not clearly defined. Other factors remaining the same, runoff per unit area may decrease with increase in slope length (Lal, 1983). In contrast, Laflen & Saveson (1970) reported that runoff increased linearly with an increase in the ratio slope steepness:slope length. Wischmeier (1966) and Wischmeier & Smith (1978) reported either negligible effects of slope length on annual runoff per unit area of cropland, or slightly lower runoff on the longer slopes during the growing seasons and slightly higher during the dormant season.

Effects of slope length on erosion

The effects of slope length on soil erosion are confounded by slope gradient, slope shape, and slope-induced alterations in soil properties. Other factors remaining the same, soil erosion supposedly increases in proportion to some power of slope length. Higher erosion on longer slopes may be due to increased runoff velocity on longer slope lengths (Kramer & Meyer, 1969), and therefore, due to increase in rill erosion (Foster *et al.*, 1977). Laflen *et al.*, (1978) observed linear increase in soil erosion with an increase in slope length. Mutchler & Greer (1980) reported that the magnitude of the slope length exponent depends on slope gradient. In Nigeria Lal (1983) observed that on bare uncultivated slopes, soil erosion increased with an increase in slope length. In the highlands of Guatemala for an Ultic Haplustalf, Akeson & Singer (1984) observed that soil loss ranged from 50.5 t ha^{-1} on 2.4 m plots to 144 t ha^{-1} on 14.7 m plots.

Because the effects of slope length on erosion are related to runoff velocity, the length-effect may be easily altered by soil and crop management e.g. by the quantity of crop residue mulch, methods of seedbed preparation, the canopy characteristics and percent ground cover. The objective of this experiment, therefore, was to evaluate the effects of slope length on runoff and erosion for different tillage methods and crops of contrasting canopy characteristics.

MATERIALS AND METHODS

Field plots were established on a newly-cleared site at the experimental farm of the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, in February 1984. The IITA is located approximately 30 km south of the upper limit of the lowland rainforest. The mean annual rainfall of about 1200 mm is received over two distinct growing seasons because of the bimodal characteristics of rainfall distribution. The first longer season lasts from about mid March to mid July, and the second shorter season from about mid August to the end of October. There is a long dry season from early November through mid March.

Field runoff plots were established on an Ibadan soil series. The soil is coarse-textured near the surface, and is characterized by a distinct gravelly horizon at about 30 to 80 cm depth. The soil is classified as an Oxic Paleustalf.

In all there were 13 runoff plots. Each plot was 4 m wide and equipped with a flume, a multi-divisor tank, and two over-flow drums. There were six plot lengths, of 60, 50, 40, 30, 20 and 10 m and two plots for each slope length. An additional plot of 25 m length was ploughed up-and-down the slope and was kept free of any vegetation cover. Slope gradient was not uniform among slope length treatments and ranged from 6.9 to 9.2%. Because of the variability in slope gradient among slope-length treatments, each plot was characterized by several slope length parameters. Slope length parameters computed were field length (*L*), length multiplied by slope gradient (%) divided by 100 (*LS*/100), and the factor *LS* of the Universal Soil Loss Equation. Plot characteristics are listed in Table 1.

Table 1 *Slope length and gradient for each experimental plot*

Slope length (m)	*Slope gradient (%)*	$\frac{LS^*}{100}$	*LS factor of USLE (metric)*	*Tillage method*
60	9.2	5.5	1.79	Ploughed
60	6.9	4.1	1.20	No-till
50	7.1	3.6	1.08	Ploughed
50	7.2	3.6	1.10	No-till
40	8.1	3.2	1.13	Ploughed
40	9.1	3.6	1.35	No-till
30	8.4	2.5	1.04	Ploughed
30	8.9	2.7	1.13	No-till
20	8.8	1.8	0.91	Ploughed
20	8.9	1.8	0.93	No-till
10	7.3	0.7	0.41	Ploughed
10	7.2	0.7	0.40	No-till
25	7.7	1.9	0.85	Ploughed (bare)

**LS/100 is the product of slope length (m) and slope gradient (%) divided by 100.*

Corn (*Zea mays*) was sown during the first and cowpea (*Vigna unguiculata*) during the second growing season. There were two methods of seedbed preparation, no-till and ploughing. The ploughing treatment consisted of disc ploughing followed by harrowing. No-till plots were sprayed with paraquat (1, l'dimethyl 4, 4' bipyridilium ion) at 0.5 kg ha^{-1} a.i., and dead weeds and the residue from previous crop were left on the surface. Seeding was done manually with a jab planter at 75 cm spacing between rows. The within-row spacing was 25 cm for corn and 15 cm for cowpea. Corn received fertilizer at the rate of 100 kg N (applied one third at seeding and two-thirds four weeks later), 26 kg P and 30 kg K per hectare. No fertilizer was applied to the following cowpea. Post-emergence weeding was done manually as and when required.

Runoff amount was measured and sediments deposited in the flume and multi-divisor tank were collected after every rainstorm event. Sediment concentration in the water runoff was determined by filtering a 0.5 l sample collected after thoroughly stirring the water in the overflow tank. Seasonal or annual runoff was expressed in mm, erosion in metric tons per hectare, and erosion:runoff ratio as kg/mm. Statistical analyses of the data were performed using seasonal data and the cumulative annual values.

RESULTS

The data reported herein are for the rain-year 1985 only. Rainfall distribution during 1985 was 1031.3 mm in the first season (March–July) and 739.8 mm in the second season (August–November). The annual rainfall exceeded the average by about 48%.

The runoff and soil erosion data for each season shown in Table 2, indicate significant differences among methods of seedbed preparation. Expectedly, there were more runoff and erosion from ploughed than from no-till plots. The effects of slope length on runoff and erosion are described below:

Slope length and runoff

In ploughed treatments, there were no consistent trends between runoff and slope length (Table 2). Slope length had negligible effects on runoff amount from ploughed plots regardless of the units in which the length was expressed e.g. in metres, as the *LS*/100 parameter, or as the *LS* factor of the Universal Soil Loss Equation (USLE).

Slope length, however, significantly affected runoff amount in no-till treatments. The runoff per unit area decreased with an increase in slope length (Table 3). The annual runoff amount in no-till treatments decreased from 44 mm for the 20 m length to about 6 mm for the 60 m length. There was also a linear decrease in total runoff amount in relation to the *LS*/100 parameter and the *LS* factor of the USLE. The highest correlation coefficient was obtained for the function relating runoff as an inverse function of slope length (Table 3).

Table 2 Effects of slope length and tillage system on runoff and soil erosion in 1985

Plot length (m)	Tillage	Runoff (mm): First season	Runoff (mm): Second season	Erosion ($t\ ha^{-1}$): First season	Erosion ($t\ ha^{-1}$): Second season
60	Ploughed	72.5	26.8	17.8	1.8
60	No-till	4.2	2.5	0.03	0.05
50	Ploughed	96.7	46.6	3.2	3.1
50	No-till	4.1	3.0	0.14	0.04
40	Ploughed	111.5	46.2	5.1	5.0
40	No-till	9.8	6.2	0.06	0.14
30	Ploughed	43.2	40.4	3.0	1.9
30	No-till	16.8	15.8	0.25	0.19
20	Ploughed	60.7	24.9	0.80	0.41
20	No-till	26.1	18.2	0.60	0.18
10	Ploughed	70.5	49.2	0.65	0.19
10*	No-till	8.9	2.3	1.35	0.01
25	Ploughed	147.1	69.2	77.1	24.9
Rainfall (mm)		1031.3	739.8	1031.3	739.8
LSD** (0.05)					
	(i) Slope length	54.8	25.3	12.3	2.8
	(ii) Tillage	31.6	14.6	7.1	1.6
	(iii) Seasons	19.8		3.31	

** *LSD values apply to the annual total (first season plus second season).*
**Storage tank leaked.*

Slope length and soil erosion

Contrary to the total seasonal or annual runoff amount, soil erosion from the ploughed plots increased as a power function of slope length. For example, the total annual soil erosion from ploughed plots increased from about 2 t ha^{-1} for the 10 m slope length to about 20 t ha^{-1} for the 60 m slope length (Table 4). There were similar responses in each season regardless of the crop. Similar functional relations were observed when erosion from ploughed plots was expressed as a function of the (*LS*/100) parameter. The response curve was, however, somewhat different when erosion from ploughed plots was expressed as a function of the *LS* factor of the USLE. The data roughly fitted a sigmoid curve with its inflection point located around an *LS* factor value of about 1.3. Similar findings have been reported earlier for data from

USA (Wischmeier & Smith, 1978; Foster *et al.*, 1977).

There was a contrasting response of erosion to slope length in no-till treatments, however. In general, erosion decreased linearly or inversely with

Table 3 *Regression equations relating slope length to runoff for no-till plots*

Regression equations	r^2
First season	
$R = 34.8 - 0.565\ (L)$	0.91
$R = -7.97 + 695\ (L)^{-1}$	0.98
$R = 43.6 - 9.95\ (LS/100)$	0.94
$R = 56.5 - 38.8\ (LS)$	0.40
Annual total	
$R = 61.6 - 1.01\ (L)$	0.92
$R = -13.9 + 1215\ (L)^{-1}$	0.95
$R = 16595\ L^{-1.92}$	0.93
$R = 134.9\ (1.05)^{-L}$	0.95
$R = 77.1 - 17.6\ (LS/100)$	0.94
$R = 99.1 - 68.1\ (LS)$	0.39

R = runoff in mm; L = slope length (m).

Table 4 *Regression equations relating slope length parameters to soil erosion from ploughed plots*

Regression equations	r^2
First season	
$E = 0.01\ L^{1.66}$	0.80
$E = 0.332\ (1.063)^{L}$	0.86
$E = 0.708\ (LS/100)^{1.55}$	0.81
$E = 0.356\ (2.037)^{LS/100}$	0.92
$E = -8.71 + 13.0\ (LS)$	0.80
$E = 2.95(LS)^{2.22}$	0.77
$E = 0.182\ (13.183)^{LS}$	0.87
Annual total	
$E = -3.12 + 0.302\ (L)$	0.71
$E = (1.06)\ (1.574)^{L}$	0.74
$E = -6.78 + 13.4\ (LS)$	0.79
$E = (0.826)\ (5.636)^{LS}$	0.61
$E = -3.24 + 3.71\ (LS/100)$	0.83

E = erosion in t ha^{-1}.

an increase in slope length (Table 5). The annual total erosion decreased from about 1.3 t ha^{-1} for 10 m slope lengths to about 0.1 t ha^{-1} for 60 m slope lengths. There was a similar response in both seasons. Erosion on

Table 5 *Regression equations relating slope erosion from no-till plots to slope length parameters*

Regression equations	r^2
First season	
$E = 1.26 - 0.0241\ (L)$	0.73
$E = -0.268 + 16.7\ (L)^{-1}$	0.99
$E = 1.48 - 0.387\ (LS/100)$	0.91
$E = 1.09 - 1.81 \log\ (LS/100)$	0.99
$E = 1.99 - 1.55\ (LS)$	0.96
$E = 0.357 - 2.68 \log\ (LS)$	0.96
Annual total	
$E = 1.38 - 0.025\ (L)$	0.82
$E = -0.167 + 16.3\ (L)^{-1}$	0.97
$E = 75.9\ L^{-1.63}$	0.88
$E = 1.58 - 0.395\ (LS/100)$	0.97
$E = 1.17 - 1.78 \log\ (LS/100)$	0.99
$E = 2.03 - 1.50\ (LS)$	0.92

no-till plots also decreased linearly or logarithmically with an increase in *LS*/100 or the *LS* factor. When soil erosion on no-till plots was plotted as a function of the *LS* factor of the USLE, erosion decreased with increasing values of *LS*, with an inflection point around an *LS* value of 1.0.

Soil erosion:runoff ratio

As for the runoff and erosion data, there was also a differential response of the soil erosion:runoff ratio to slope length for the two tillage methods. The soil erosion:runoff ratio increased as a power function of slope length for ploughed treatments (Table 6). During the first season, for example, the erosion:runoff ratio increased from about 6 for a slope length of 10 m to about 250 for a slope length of 30 m. There was an identical response in both seasons.

The erosion:runoff ratio, however, decreased almost inversely with increase in slope length for the no-till treatment (Table 6). The erosion:runoff ratio decreased from about 24 for the 20 m length to about 7 for the 60 m length. There was, however, an exceptionally high value for the 50 m no-till plot. The latter may be due to soil variability.

CONCLUSIONS

The preliminary data presented about support the following conclusions:

(a) The effects of slope length on runoff and soil erosion depend on the tillage method.

Table 6 *Empirical equations relating the erosion:runoff ratio to slope length parameters*

Tillage method	*Regression equations*	r^2
First season		
(a) Ploughed	$E{:}R = 0.25\ L^{1.49}$	0.69
	$E{:}R = 5.89\ (1.06)^L$	0.72
(b) No-till	$E{:}R = -29.6 + 1850\ (L)^{-1}$	0.85
Annual total		
(a) Ploughed	$E{:}R = -24.0 + 2.8\ L$	0.60
	$E{:}R = 11(1.042)^L$	0.70
(b) No-till	$E{:}R = -21.3 + 1342\ (L)^{-1}$	0.85

E:R = erosion:runoff ratio (kg mm^{-1}*).*

(b) For the plough-based method of seedbed preparation, slope length has no effect on runoff. For the no-till method of seedbed preparation, however, runoff decreased with an increase in slope length.

(c) For the plough-based system, soil erosion increases as a power function of slope length. For the no-till system, erosion decreases linearly or inversely with an increase in slope length.

(d) The erosion:runoff ratio increased as a power function of slope length for ploughed land, and decreased inversely with increasing slope length for the no-till system of seedbed preparation.

(e) The differential effects of slope length on runoff and erosion may be related to runoff velocity. The time of concentration is longer on long slopes than for short slope lengths, and shorter on ploughed than on no-till plots.

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REFERENCES

Akeson, M. & Singer, M. J. (1984) A preliminary length factor for erosion on steep slopes in Guatemala and its use to evaluate "curvas a nivel." *Geoderma* 33, 265.

Bergsma, E. (1985) Classes of relief susceptibility for surface erosion. In: *Soil Erosion and Conservation*, (ed. by S. A. El-Swaify, W. C. Moldenhauer, & Al Lo), p. 432.

Soil Conservation Society of America, Ankeny, Iowa, USA.

De Ploey, J. (1984) Hydraulics of runoff and loess loam depositon. *Earth Sur. Processes and Landforms* **9**, 533.

Foster, G. R., Meyer, L. D., & Onstad, C. A. (1977) A runoff velocity factor and variable slope length exponents for soil loss estimates. *Trans. Am. Soc. Agric. Engrs* **20**, 683.

Gilley, J. E., Woolhiser, D. A. & McWhorter, D. B. (1985) Inter-rill soil erosion. Part II: Testing and use of model equations. *Trans. Am. Soc. Agric. Engrs* **28**, 154.

Hahn, D. T., Moldenhauer, W. C. & Roth, C. B. (1985) Slope gradient effect on erosion of reclaimed soil. *Trans. Am. Soc. Agric. Engrs* **28** (3), 805.

Kramer, L. A. & Meyer, L. D. (1969) Small amount of surface mulch reduce soil erosion and runoff velocity. *Trans. Am. Soc. Agric. Engrs* **12**, 638, 645.

Laflen, J. M. & Saveson, J. L. (1970) Surface runoff from graded lands of low slopes. *Trans. Am. Soc. Agric. Engrs* **13**, 340.

Laflen, J. M. et al. (1978) Au please give details of cited Reference.

Lal, R. (1983) Effects of slope length on runoff from Alfisols in Western Nigeria. *Geoderma* **31**, 185.

Lal, R. (1984) Effects of slope length on soil loss from Alfisols in Western Nigeria. *Geoderma* **33**, 181.

Mutchler, C. K. & Greer, J. D. (1980) Effect of slope length on erosion from low slopes. *Trans. Am. Soc. Agric. Engrs* **23**, 866.

Poesen, J. (1985) An improved splash transport model. *Z. Geomorph.* **29**, 193.

Poesen, J. (1986) Surface sealing as influenced by slope angle and position of simulated stones in the top layer of loose sediments. *Earth Sur. Processes and Landforms* **11**, 1.

Schroeder, S. A. (1987) Slope gradient effect on erosion of reshaped spoil. *Soil Sci. Soc. Am. J.* **51**, 405.

Smith, D. D. & Wischmeier, W. H. (1957) Factors affecting sheet and rill erosion. *Trans. Am. Geophys. Union* **38**, 889.

Tacconi, P., Billi, P. & Montani, C. (1982) Slope length and sediment yield from hilly cropland. In: *Recent Advances in the Explanation and Prediction of Erosion and Sediment Yield* (Proc. Exeter Symp., July 1982), 199-207. *IAHS Publ. no. 137.*

Van Liew, M. W. & Saxton, K. E. (1983) Slope steepness and incorporated residue effects on rill erosion. *Am. Soc. Agric. Engrs Paper no. 2131*, 25 pp.

Wischmeier, W. H. (1966) Relation of field plot runoff to management and physical factors. *Soil Sci. Soc. Am. Proc.* **30**, 272.

Wischmeier, W. H. & Smith, D. D. (1978) Predicting Rainfall Erosion Losses - *A Guide to Conservation Planning.* USDA-Agric. Handbook no. 537, Washington, DC.

Wischmeier, W. H., Smith, D. D. & Uhland, R. E. (1958) Evaluation of factors in the soil loss equation. *Agric. Eng.* **39**, 458, 474.