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Evaluation of factors influencing water erosion in West Africa using rainfall simulation

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ABSTRACT In order to provide an improved understanding of the factors influencing water erosion in western Africa, field studies were carried out in three countries (Ivory Coast, Upper Volta and Niger). Two types of rainfall simulator were used. Particular attention was given to the intensity-duration curves, the kinetic energy of the storms, and to the range of antecedent soil moisture conditions. Treatments were selected in accordance with the farming systems prevailing in the study areas. Results were consistent with those obtained under natural rainfall. They suggested that surface gravel and cobbles are very effective in reducing erosion. In the humid tropics, the erosive effects of storm rainfall are offset by the natural protection provided by the vegetative cover. The effectiveness of traditional conservative practices depends upon the soil water infiltration. Above certain threshold values, ridges collapse and as a result erosion is strongly enhanced. Likewise, the efficiency of residue mulch depends upon the texture of the topsoil. Consequently, the indiscriminant use of the Universal Soil Loss Equation which includes factors which are assumed to be independent can be highly hazardous.

Estimation des facteurs de l'érosion hydrique en Afrique de l'Ouest à l'aide de la simulation de pluies

RESUME Des travaux de terrain ont été menés dans trois pays (Côte d'Ivoire, Haute Volta et Niger) afin de fournir davantage de données concernant les différents facteurs qui interviennent sur l'érosion hydrique en Afrique de l'Ouest. Deux types de simulateurs de pluies ont été utilisés. Une grande attention a été portée aux courbes intensité-durée, à l'énergie cinétique des pluies, et à la gamme d'humidités avant les averses. Les traitements ont été choisis en fonction des systèmes culturaux qui prédominent dans les diverses régions d'études. Les résultats sont conformes à ceux obtenus sous pluies naturelles. Ils expriment l'importance des éléments grossiers superficiels quant à la conservation des sols. En milieu tropical humide une protection naturelle est assurée par le couvert végétal qui compense ainsi les effets néfastes des pluies très violentes. L'influence des techniques traditionnelles de lutte anti-érosive est liée aux quantités d'eau infiltrée: à partir d'un certain seuil, les billons s'écroulent et l'érosion subit alors une vive augmentation. De même l'effet de l'utilisation de résidus de culture comme paillage dépend de la texture du matériel pédologique superficiel. Ainsi, l'utilisation, sans discernement, de l'équation universelle des pertes en terres dont les facteurs sont supposés indépendants peut être très hasardeuse.

INTRODUCTION

Land degradation has increased noticeably in Africa during the last few decades through a breakdown in the equilibrium between population densities and traditional farming systems. Yet information concerning the extent, causes, and control of water erosion in western Africa still remains fragmentary and limited. This can be partly ascribed to the dependence upon field runoff plots under natural rainfall as the main data source (Lal, 1976; Roose, 1977). These are costly and demand long periods of observation. Because of financial limitations, measurements can be conducted only on a restricted number of sites.

Rainfall simulation permits the collection of large quantities of data within a short period from various remote experimental sites. Furthermore, more control can be exercised over the parameters. This method has therefore been employed and adapted to African conditions. Experiments were conducted in areas ranging from the rainforest of Ivory Coast to the desert in Niger (Fig.1). The purpose of this paper is to present the results of these experiments relevant to the extent of erosion and to its control.

EXPERIMENTAL BACKGROUND

Method

The research strategy employed in this study aimed to simulate realistic conditions. Owing to the great environmental variations from one site to another, a standard procedure could not be followed. Climatic data were used as guidelines. Each experimental programme was established by reference to the intensity-duration curves corresponding to the experimental area. Thus each run did not last longer than the analogous natural storm with a 10 year return period. The same rule was adopted to limit the daily cumulative rainfall. Likewise the amount of rainfall simulated during the whole test period did not exceed the mean annual rainfall. The Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) was also employed so that results could be compared with data from other sources.

Treatments

On each site, treatments included:

(a) a vegetated treatment where the natural cover was preserved,

(b) a standard surface treatment produced by removing the vegetation and by hoeing up and down the upper 10 cm. This represented conventional seedbed conditions.

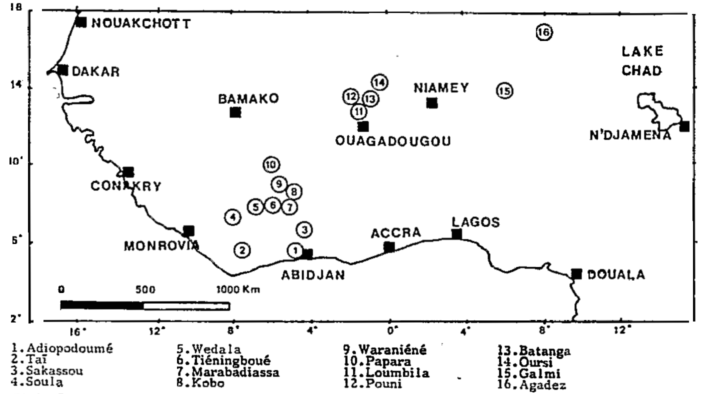

FIG.1 Location map for the rainfall simulation erosion studies in West Africa.

In addition, other treatments were selected in accordance with the farming systems prevailing in the study areas. Accordingly, traditional tillage practices including simple and tied mounding, down-hill and contour crop-ridging were tested. Moreover, in order to determine the effects of mulching on soil conservation, residue mulches were selected according to the local crops, namely, pineapple, sugarcane and millet straw.

Each plot was subjected to an initial rainfall simulation in very dry conditions because experiments were conducted during the dry season. A wide range of antecedent soil moisture conditions was then achieved by planning drying periods which varied from 0.5 h to more than 1 week. Sequences of rainfall inputs were consistent with available climatic data. The rainfall simulations were applied at each site within a period of a month. Intensities of 30, 45, 60, 90 and 120 mm h^{-1} were selected.

Rainfall simulators

Two types of rainfall simulators were used separately or simultaneously depending on sites. One was a rotating-boom simulator capable of applying rainfall rates ranging from 30 to 120 mm h^{-1} (Swanson, 1965). It comprises 30 nozzles supported by 10 arms radiating from a central stem. The nozzles spray downward from an average height of 3.5 m. The 200 m^2 sprinkled area includes two 50 m^2 plots (5 x 10 m, with the long axis parallel to the slope). Up to now, this heavy equipment has been transported from Adiopodoumé (Ivory Coast) to 10 experimental sites as remote as Galmi (Niger, see location map, Fig.1).

A more easily transportable piece of equipment is the sprinkling infiltrometer (Asseline & Valentin, 1978). It consists of a telescopic tower on which one single nozzle is mounted. A large canvas cover encloses the experimental area to exclude wind. The perpendicular distance from the nozzle to the impact surface area is 3.7 m. Moved by an adaptated windscreen wiper motor, the nozzle oscillates across the plot. The angle of oscillation is altered by modifying the length of the drive shaft and can be rapidly regulated from the ground. Corresponding intensities range from 30 to 140 mm h^{-1}. Accordingly, the buffer ring zone around the 1 m^2 plot varies from 2.5 to 8 m^2.

Both sprinklers were designed to reproduce the characteristics of natural storms. A study of drop size distributions and impact velocities was therefore undertaken. At the time when the rotating-boom simulator was calibrated, the results of the measurements of the kinetic energy of natural rainfall in Abidjan were not available. American data were therefore used. More recently designed, the sprinkling infiltrometer appears to be better adapted to West African conditions. For both sprinklers the best approximations were achieved at high rates of application (Table 1). These values were used to compute the erosion indices of the USLE for simulated storms.

TABLE 1 Kinetic energies of natural and artificial rainfall and spray

	Intensities (mm h^{-1}):					*Source*
	30	*45*	*60*	*90*	*120*	
NATURAL RAINFALL						
United States	*25.2*	*26.8*	*27.9*	*29.5*	*30.6*	*Wischmeier & Smith (1958)*
Ivory Coast	*18.3*	*19.6*	*20.4*	*21.7*	*22.6*	*Valentin (1981)*
ARTIFICIAL RAINFALL						
Rotating boom-simulator	*36.1*	*40.7*	*40.9*	*31.4*	*32.4*	*Valentin (1978)*
Sprinkling infiltrometer	*14.7*	*17.8*	*18.9*	*20.4*	*22.8*	*Ruiz Figueroa (1983)*

Field measurements

Plot surface features In order to illustrate the influence of surface gravel and cobbles on soil conservation, samples were collected from the tilled layer. The percentage of coarse fragments was determined by weighing. Glao *et al.* (1983) found a strong correlation between the values (G%) obtained with this convenient method and the percentage of surface gravel and cobbles (S%) measured by the pin-point meter method which is more arduous. On completion of the experiments, undisturbed surface samples were collected for micromorphological analysis to assess the degree of soil surface sealing.

Application, runoff and discharge rates Similar field measurement procedures were adopted for both sprinklers.

For the rotating-boom simulator, two raingauge troughs (0.05 m x 4.00 m) were placed across each plot to check the rainfall amount. A third, located between the two plots, was connected to a sensitive rainfall recorder to measure the application rate. A wind gauge was used to ensure that wind speeds did not exceed 2 m s^{-1}. Above this limit, the rainfall distribution was not found to be sufficiently homogeneous. On each plot, runoff intensities (mm h^{-1}) were measured with a very sensitive water level recorder so that variations in depth and time of 0.05 mm and 15 s respectively could be discriminated on the runoff hydrograph. Periodically, sediment samples were manually collected in 4-l plastic bottles. Sampling intervals were dependent on changes in the runoff rate. After every runoff period, sediment trapped in the flume was weighed.

In the case of the sprinkling infiltrometer, sprinkling intensity was measured prior to each run by placing a 1 m^2 pan over the plot, and adjusted to the required rate. Runoff was collected in a reservoir which also was equipped with a very sensitive water-level recorder. Sediment samples were manually collected from the flume in 0.3-l bottles at intervals that depended on runoff rate.

Data analysis Rainfall records were converted to hyetographs. Hydrographs and runoff volumes were obtained from the water level records from each flume. These runoff hydrographs were combined with sediment concentration values to compute sediment discharge rates and total soil loss. USLE erosion factors were then calculated.

RESULTS AND DISCUSSION

Potential water erosion

Erosion rates from bare and tilled soils are presented in Table 2, for various ecological zones. This table does not include results from soils where the coarse fraction exceeded 5%.

Schematically, three climatic zones can be distinguished:

(a) Hyper humid regions where $R > 800$ and the mean annual rainfall exceeds 1600 mm. Topography is usually hilly and these factors combine to give a high erosion potential, $E > 50$ t ha^{-1}year^{-1}.

(b) Humid and sub-humid regions where $400 < R < 800$. Slopes are generally gentle. Consequently, potential erosion is moderate, $20 < E < 50$ t ha^{-1}year^{-1}.

(c) Semiarid, arid and hyper-arid regions where $R < 400$. Slopes are scarcely marked. Owing to their low organic matter contents, most soils are subjected to surface sealing which enhances their resistance to splash and sheet erosion (Valentin, 1981). As a result, potential erosion rates predicted from the runoff plots are slight to moderate: $E < 20$ t ha^{-1}year^{-1}.

These results demonstrate that the most important parameter in influencing soil erosion by water is the rainfall factor R, which estimates the mean annual erosive power of raindrop impact. Slight changes in slope gradient, and in organic matter content are also responsible, but to a lesser extent, for variations in erosion rates. Little relationship appears to exist between soil loss and pedological soil type.

Since the results obtained with two different slope lengths (1 and 10 m) are consistent, rill erosion is either limited or is restricted to longer slopes. Only measurements at the basin scale

TABLE 2 The effects of various factors on soil loss from bare and tilled tropical soils under simulated rainfall

*Site**	*Soil unit (FAO)*	*o.m. (%)*	*Slope (m m^{-1})*	*R*	*E (t ha^{-1}year^{-1})*
1[†][°]	*Ochric ferralsol (eroded)*	*1.3*	*0.070*	*1030*	*129.9*
1[§]	*Ochric ferralsol (recently cleared)*	*2.5*	*0.070*	*1030*	*79.6*
2[†]	*Plinthic ferralsol*	*2.4*	*0.073*	*920*	*73.3*
10[§]	*Ochric gleysol*	*1.5*	*0.008*	*680*	*18.6*
3[†]	*Ochric ferralsol*	*1.7*	*0.028*	*625*	*20.2*
5[§]	*Ochric ferralsol*	*2.6*	*0.030*	*625*	*24.6*
7[§]	*Ochric ferralsol*	*1.4*	*0.030*	*625*	*30.3*
13[†]	*Vertic cambisol*	*1.5*	*0.005*	*330*	*2.2*
15[†]	*Vertic cambisol*	*0.4*	*0.038*	*300*	*7.7*
15[†]	*Ferric luvisol*	*0.6*	*0.028*	*300*	*6.1*
14[†]	*Xerosol*	*0.4*	*0.033*	*225*	*10.7*
14[†]	*Ferric luvisol*	*0.9*	*0.004*	*225*	*6.0*
14[†]	*Arenosol*	*0.5*	*0.011*	*225*	*1.4*
16[§]	*Dystric fluvisol*	*0.7*	*0.025*	*80*	*5.4*
16[§]	*Dystric fluvisol*	*0.1*	*0.014*	*80*	*1.6*

R is the rainfall erosion index of the USLE computed after Roose (1977).
E is the computed soil loss per unit area per year.
o.m. is the organic matter content in the tilled layer.
* *The number refers to the location map (Fig.1).*
[†] *With the rotating-boom simulator.*
[§] *With the sprinkling infiltrometer.*
[°] *After Roose & Asseline (1978).*

could solve this scale problem.

For a given region, the results furnished by the rainfall simulators are within the range of the data obtained under natural rainfall (Table 3). Rainfall simulation therefore appears to provide relevant erosion measurements.

Natural protection of soils

Surface gravel and cobbles Many cultivated tropical soils cannot be properly considered as bare soils since they are partially or almost completely covered with gravel or cobbles. **The results** from 17 1-m^2 plots, located within the three countries, with surface coarse fractions (G%) ranging from 5% to 79% (desert pavement in Agadez), were used to establish a regression equation and to predict the relative importance of this factor in terms of erosion reduction C (Fig.2):

$$C = 0.73 \exp(-0.06\ G) \qquad n = 17 \qquad r^2 = 0.96$$

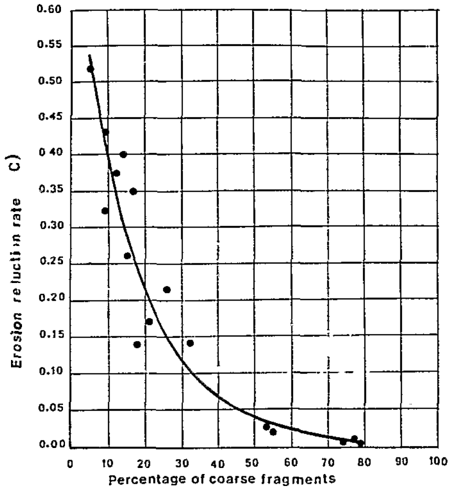

FIG.2 The influence of coarse surface fragments on the erosion reduction factor (C).

Vegetative cover In the humid tropics, soil is naturally protected from the erosive effects of storm rainfall by the vegetative cover. It must be noted that a dense herbaceous cover can be as effective as rainforest (Table 4). In the latter case, trees play a minor role in protecting soil when compared with litter and root mats. A theoretical study based upon the size and the velocity of the drops intercepted by a tree indicated that the kinetic energy of the intercepted rainfall is not significantly different from the energy of free-falling drops (Collinet & Valentin 1980). Consequently, slash-and-burn clearing, which does not seriously alter the density of cover because of an abundance of weeds, produces little change in soil loss.

TABLE 3 Examples of erosion rates measured under natural rainfall in West Africa

Location	*R*	*Slope (m m^{-1})*	*Erosion rate (t ha^{-1}year^{-1})*	*Source*
*Adiopodoumé**	*1030*	*0.07*	*69-150*	*Roose (1977)*
*Bouaké**	*580*	*0.04*	*11-52*	*Roose (1981)*
Allokoto[†]	*200*	*0.03*	*4-19*	*Delwaulle (1973)*

R is the rainfall erosion index of the USLE.
* *Bare soil.*
[†] *Traditionally cultivated.*

In drier regions, greater variations of the reduction factor C are observed. Two examples are shown in Table 4. The first relates to the removal of the vegetation cover by a bushfire which produced an 80-fold increase in erosion rates when compared to the undamaged herbaceous cover. The second reflects the influence of drought where seasonal changes promote noticeable variations in the protecting effect of the cover. Thus, in the Sahelian zone, soil losses are almost 50 times greater under scanty vegetation than under a dense herbaceous layer, all other conditions (soil moisture, sequence of runs etc) being the same.

TABLE 4 The erosion reduction factor C for various natural vegetative covers

Climatic zone	*Location*	*Type of vegetative cover*	*C*
Hyper-humid	*Taï*	*Tropical rainforest**	*0.002*
	Taï	*After traditional clearing*†	*0.010*
Humid	*Sakassou*	*Herbaceous, very dense*†	*0.002*
	Sakasou	*After bush fire*†	*0.160*
Semiarid	*Oursi*	*Herbaceous, dense*†	*0.010*
	Oursi	*Scanty, after drought*†	*0.470*

* *Under natural rainfall.*
† *With the rotating-boom simulator.*

Erosion control

Traditional conservation practices Throughout West Africa two main traditional practices are applied, namely, crop-ridging and mounding. The lowest values of factor P, corresponding to the most effective techniques, were registered for 1-year-old contour and down-hill crop-ridges, and for simple mounding (Table 5). These three systems reduce runoff velocity. However, recently built contour crop-ridges and tied mounds accumulate water so that once some threshold of rainfall depth is reached, they may collapse. When that happens, erosion rates increase rapidly and can even surpass those of the reference plot (Fig.3). Loose material associated with new down-hill ridges is easily detached and as a result their conservation effect is very limited.

TABLE 5 Erosion reduction factors (P) for various traditional control practices

Location	*Erosion control practice*	*P*
Taï	*Simple mounding*	*0.12*
Pouni	*Tied mounding*	*0.67*
Batanga	*Tied mounding*	*0.30*
Galmi	*Contour ridging: new ridges*	*0.28*
Galmi	*Contour ridging: old ridges*	*0.08*
Galmi	*Down-hill ridging: new ridges*	*0.75*
Galmi	*Down-hill ridging: old ridges*	*0.22*

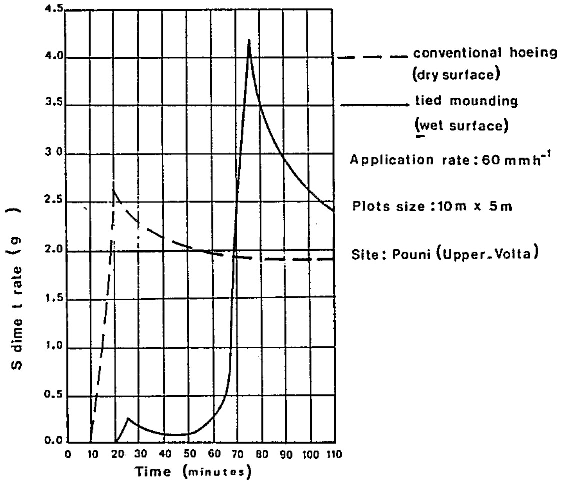

FIG.3 Sedigraphs from a conventionally hoed plot and from a tied mounded plot.

These results suggest that P values are not independent of the hydrological properties of soils or of the climatic sequences.

Plant residue mulches Large variations are observed among the values of the erosion reduction factor C (Table 6). They cannot be ascribed to the type of mulch since there was 100% surface cover in all cases. However, they may result from the difference between the underlying soil type. Mulching has been found to be more effective on sandy soils, namely for soils which are the most susceptible to splash erosion (Ekern, 1956; Mazurak & Mosher, 1968). On the other hand, mulch cover has been observed to be less effective on soils which slake (e.g. vertic soils) (Valentin, 1981). Therefore, mulching should not be used regardless of the properties of the topsoil.

CONCLUSION

Field studies using rainfall simulation can supply pertinent information regarding erosion measurement and control, provided that the experimental procedure is adapted to the local climatic conditions and the tests are conducted on appropriate plots. Plots of 1 m^2 are, for example, inadequate to assess the effect of conservation practices. The results suggest that caution is required when deriving

TABLE 6 Combined surface texture and mulch effects on factor C

Location	*Soil unit (FAO)*	*Textural class (USDA)*	*Residue mulch*	*C*
Adiopodoumé[*]	*Ochric ferralsol*	*Loamy sand*	*Pineapple*	10^{-4}
Marabadiassa[§]	*Ochric ferralsol*	*Sandy loam*	*Sugarcane*	10^{-2}
Pouni[†]	*Ferric luvisol*	*Sandy clay loam*	*Millet straw*	*0.17*
Batanga[†]	*Vertic cambisol*	*Sandy clay*	*Millet straw*	*0.38*

[*] *Under natural rainfall.*
[§] *With the sprinkling infiltrometer.*
[†] *With the rotating-boom simulator.*

local C and P values for completely different situations. Thus, application by conservation planners of the USLE "to project erosion data to the many localities and conditions that have not been directly represented in the research" (Wischmeier & Smith, 1978) can be considered as hazardous. As a result further information concerning the interactions between erosion factors is needed. This can best be achieved using appropriate rainfall simulators.

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