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Evaluation of water erosion factors in western Africa using rainfall simulation

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ABSTRACT. In order to better document the causative parameters of water erosion in western Africa, field studies were carried out in three countries (Ivory Coast, Upper-Volta and Niger). Two types of rainfall simulators were used. Great attention was paid on intensity-duration curves, kinetic energy of storms, and on the range of antecedent soil moistures. 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 downpours are offset by the natural protection provided by the vegetative cover. The influence of the traditional conservative practices depends upon the soil water intake: above 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 indiscriminated use of the Universal Soil Loss Equation which includes factors supposed 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'utilisaton de résidus de culture comme paillage dépend de la texture du matériau 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 been promoted in Africa for few decades by the breakdown in the equilibrium between population densities and the traditional farming systems, combined with unsuitable land use techniques. Yet the need for such works, the available documentation of the extent, causes, and control of water erosion in western Africa still remains fragmentary and limited. This serious gap can be partly ascribed to the method which has been selected for previous works (Lal 1976, Roose 1977) and which actually is time and money consuming: it consists in collecting data from runoff-erosion plots under natural rainfall within several years. As a result, measurements can be conducted on a restricted number of sites. Within a short period, rainfall simulation permits to collect numerous data, on various remote experimental sites and controlling more parameters. This method was therefore preferred and adapted to African conditions. Experiments were conducted from the rainforest in Ivory Coast to the desert in Niger (fig.1). This paper purposes to present the main results relevant to the extent of erosion and its control.

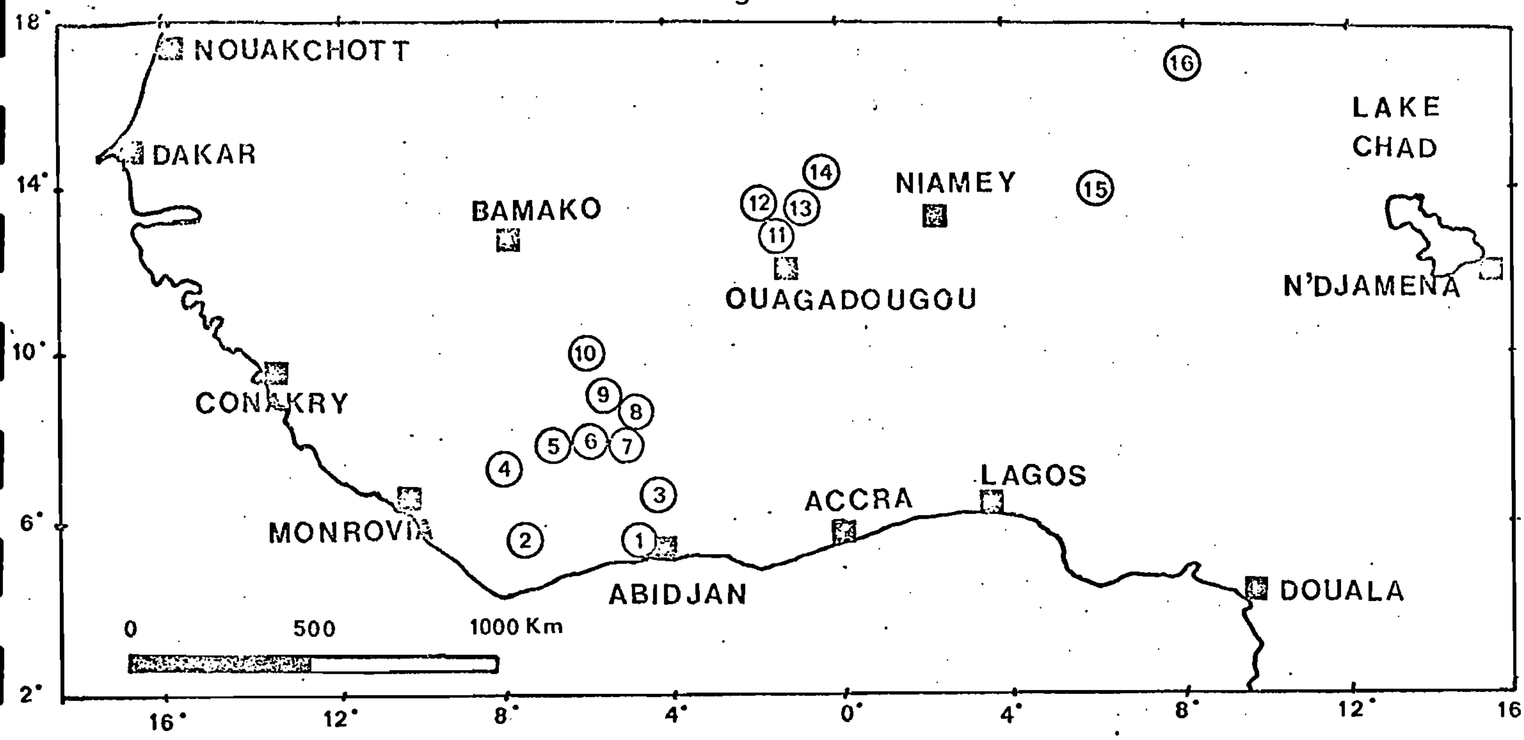

FIG.1 Location map for erosion studies using rainfall simulation in west Africa

1.Adiopodoumé	5.Wedala	9.Waraniéné	13.Batanga
2.Taï	6.Tiéningboué	10.Papara	14.Oursi
3.Sakassou	7.Marabadiassa	11.Loumbila	15.Galmi
4.Soula	8.Kobo	12.Pouni	16.Agadez

EXPERIMENTAL BACKGROUND

Method

The research plan of 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 plan was laid down in reference to the intensity-duration curves corresponding to the experimental area. Thus each run did not last longer than the analogous natural storm of decennial occurence. The same rule was followed to limit the daily cumulative rainfall. Likewise the amount of rainfall simulated during the whole tests period did not exceed the mean annual rainfall. The USLE (Universal Soil Loss Equation, Wischmeier & Smith 1960) was used so that results could be compared with data from other authors.

Treatments

On each site, treatments included:

(a) a vegetation 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. The plot was placed in conventional seedbed conditions.

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

After treatment, each plot was subjected to an initial rainfalll simulation in very dry conditions because experiments were conducted during dry seasons. A wide range of antecedent soil moisture conditions was then achieved by planning drying periods which varied from ½ h to more than one week. Sequences of rainfall inputs were arranged consistently with available climatic data. The rainfall simulations were applied for each site within a period of a month. Intensities of 30, 45, 60, 90 and 120 mm h^{-1} were selected.

<u>Rainfall simulators</u>

The equipment used included two types of rainfall simulators which were used separately or simultaneously depending on sites.

The first one is a rotating-boom simulator capable of applying rainfall rates ranging from 30 to 120 mm h^{-1} (Swanson 1965). Thirty nozzles are 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 dragged for 10 expeditions from Adiopodoumé (Ivory Coast) to experimental sites as remote as Galmi (Niger-see location map, fig.1).

More easily transportable is the sprinkling infiltrometer (Asseline & Valentin 1978). It consists of a telescoping tower on which one single nozzle is mounted. A large canvas cover encloses the experimental area to prevent wind distorsion of the spray. The perpendicular distance from the nozzle to the impact surface area is 3.7 m. Moved by an adaptated wind-screen wiper, the nozzle is oscillated across the plot.

The angle of oscillation is altered by modifying the length of the driving 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 m^2 to 8 m^2.

The calibration of both equipments was designed to achieve characteristics similar to natural storms. A study was therefore carried out on drop size distributions and impact velocities. At the moment when the rotating-boom simulator was calibrated, first results on kinetic energies of natural rainfall in Abidjan were not yet available. American data were therefore used. More recently designed, the sprinkling infiltrometer appears to be better adapted to west African conditions. For both equipments, best approximations were achieved at high rates of application (table 1). These values were used to compute the erosion indexes of the USLE for simulated storms.

Table 1 Kinetic energies of natural 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
Spray:						
- 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 layers. The percentages of coarse fragments fraction were determined by weighing. Glao et al (1983) found a strong correlation between the values (G %) obtained with this convenient method and the percentages of surface gravel and cobbles (S %) measured with the pin-point meter method that is more arduous:

$$n = 80 \qquad r^2 = 0.88 \qquad S = G - 0.10 \qquad (1)$$

After the experiments, undisturbed surface samples were collected for micromorphological analysis to appreciate the seriousness of soil surface sealing.

Application, runoff and discharge rate   Field measurement rules are similar for both equipments:

(a) rotating-boom simulator: two raingauges (0.05 m x 4.00 m) were placed across each plot to check the rainfall amount. A third one, placed between the two plots, was connected to a fast-turning rain recorder to measure the application rate. A wind gauge was used to ascertain whether wind speeds did not exceed 2 m s^{-1}. Above this limit, rainfall distribution was not found to be sufficiently homogeneous. On each plot, runoff intensities were measured with a very sensitive water-level recorder so that changes of 0.05 mm and 15 s were noticeable 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.

(b) sprinkling infiltrometer: prior to each run, spray intensity was measured by placing a 1 m^2 pan over the plot, and then 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 of each flume. These runoff hydrographs were combined to sediment concentration values to compute sediment discharge rates and total soil loss. Erosion factors were then analysed as an application of the USLE.

RESULTS AND DISCUSSION

Potential water erosion

Erosion rates from bare and tilled soils are presented in table 2, for various ecological zones. This table doen't show results from soils where coarse fragments fractions exceed 5%.

Table 2 Effects of various erosion factors on soil losses from bare and tilled tropical soils

Site*	soil unit (F.A.O.)	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 and per year
o.m. is the organic matter content in the tilled layer

* : number refers to the location map (figure 1)
\+ : with the rainfall rotating boom simulator
§ : with the sprinkling infiltrometer
° : after Roose & Asseline 1978

Schematically, three large zones can be distinguished:

(a) hyperhumide regions: $R > 800$ (namely, the mean annual rainfall exceeds 1 600 mm). Most often, topography is hilly. These combined factors induce severe potential erosion: $E > 50$ t $ha^{-1} year^{-1}$

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

(c) semi-arid, arid and hyper-arid regions: $R < 400$. 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 predicted from runoff plots are slight to moderate: $E < 20$ t $ha^{-1} year^{-1}$.

These results demonstrate that the parameter which most influences soil erosion by water is the rainfall factor R, which estimates the mean annual erosive power of raindrop impact. Slight changes in slope gradients, and in organic matter contents are also responsible, but to a lesser extent, for variations in erosion values. The relation between the soil losses and the pedological soil types appears to be poor.

Since the results obtained with two different slope lengths (1 m and 10 m) are consistent, rill erosion either is limited or occurs on longer slopes. But only measurements on basins could solve this scale problem.

For a given region, the results furnished by simulating rainfall are within the ranges of the data obtained under natural rainfall (table 3). Rainfall simulation appears to be therefore relevant to erosion measurement.

Table 3 Few 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 197[illegible]

R is the rainfall erosion index of the USLE

* : bare soil   + : traditionally cultivated

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 plots of 1 m^2, scattered over the three countries, with surface coarse fragments 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):

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

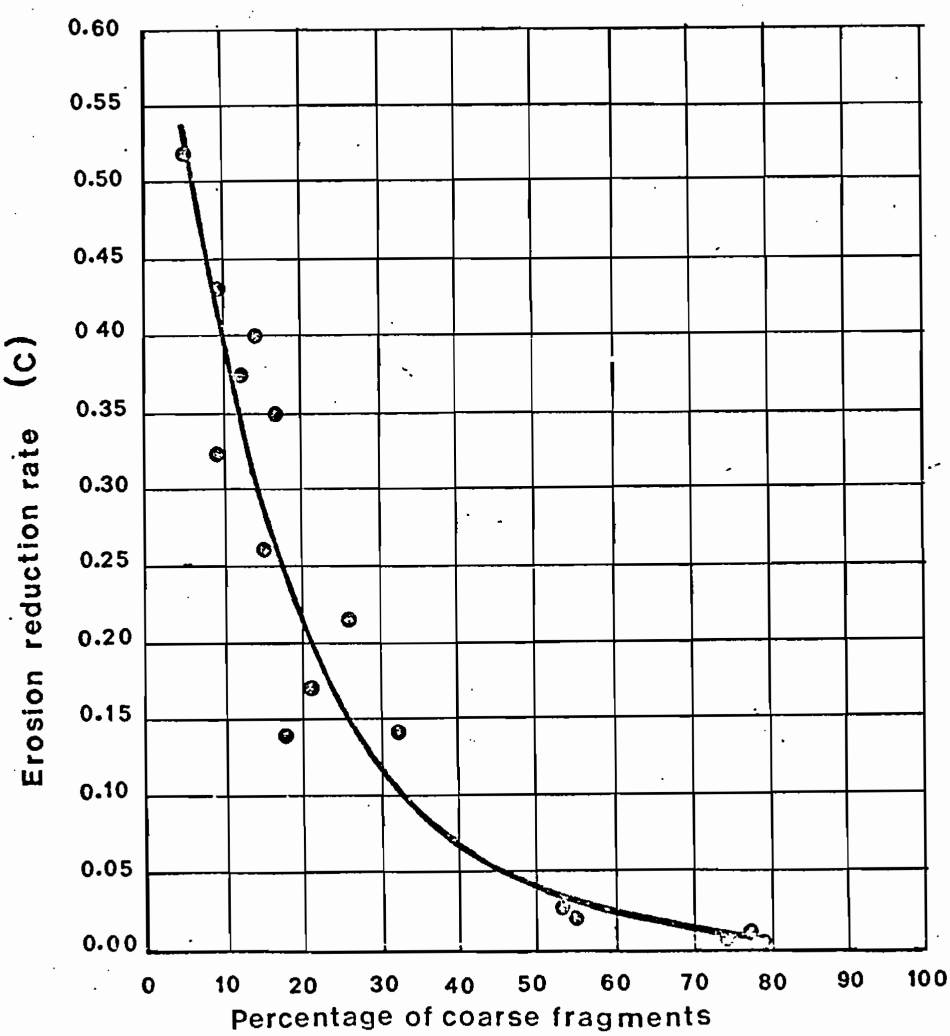

FIG. 2 Influence of coarse fragments on the erosion reduction rate

<u>Vegetative cover</u> In humid Tropics, soil is naturally protected from the erosive effects of downpours by the vegetative cover. It must be noted that a dense herbaceous layer can be as effective than rainforest (table 4). Actually, in this case, trees play a minor role in protecting soil as 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 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 doesn't seriously alter the density of cover because of abundance of weeds produces little change in soil losses.

In drier regions, greater variations of the reduction factor C are observed. Two examples are shown in table 4:

(i) bush-fire: prior to runs bush-fire induces soil losses which are 80 times more important than those registered under undamaged herbaceous cover,

(ii) drought: seasonal changes promote noticeable variations in the protecting effect of the cover. Thus, in the Sahelian

Table 4 Erosion reduction factor C for various vegetative covers

Climatic zone	location	type of vegetative cover	C
Hyper-humid	Taï	tropical rain forest*	0.002
	"	after traditional clearing+	0.010
Humid	Sakassou	herbaceous, very dense+	0.002
	"	after bush fire+	0.160
Semi-arid	Oursi	herbaceous, dense+	0.010
	"	scanty, after drought+	0.470

* : under natural rainfall + : with the rotating-boom simulator

zone, soil losses are almost 50 times more serious under scanty vegetation than under a dense herbaceous layer, all other conditions (soil moisture, sequence of runs,...) being the same.

Erosion control

Traditional conservation practices Throughout western Africa two main traditional practices are applied: ridging and mounding. The lowest values of factor P, corresponding to the most effective techniques, were registered for one-year-old contour and down-hill ridges, and for simple mounding (table 5). These three sytems have in common to reduce runoff velocity without stopping it. In the opposite, recently built contour ridges and tied mounds accumulate water so that, beyond a certain amount of rainfall, once some threshold is reached, these obstacles collapse. Consequently, sediment rates strongly increase and can even surpass those of the reference plot (fig.3). Loose materials of new down-hill ridges are easily detached; as a result, their conservative effect is very limited.

Table 5 Erosion reduction factor P for various traditional control pratices

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
"	" " old ridges	0.08
"	down-hill ridging: new ridges	0.75
"	" " old ridges	0.22

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

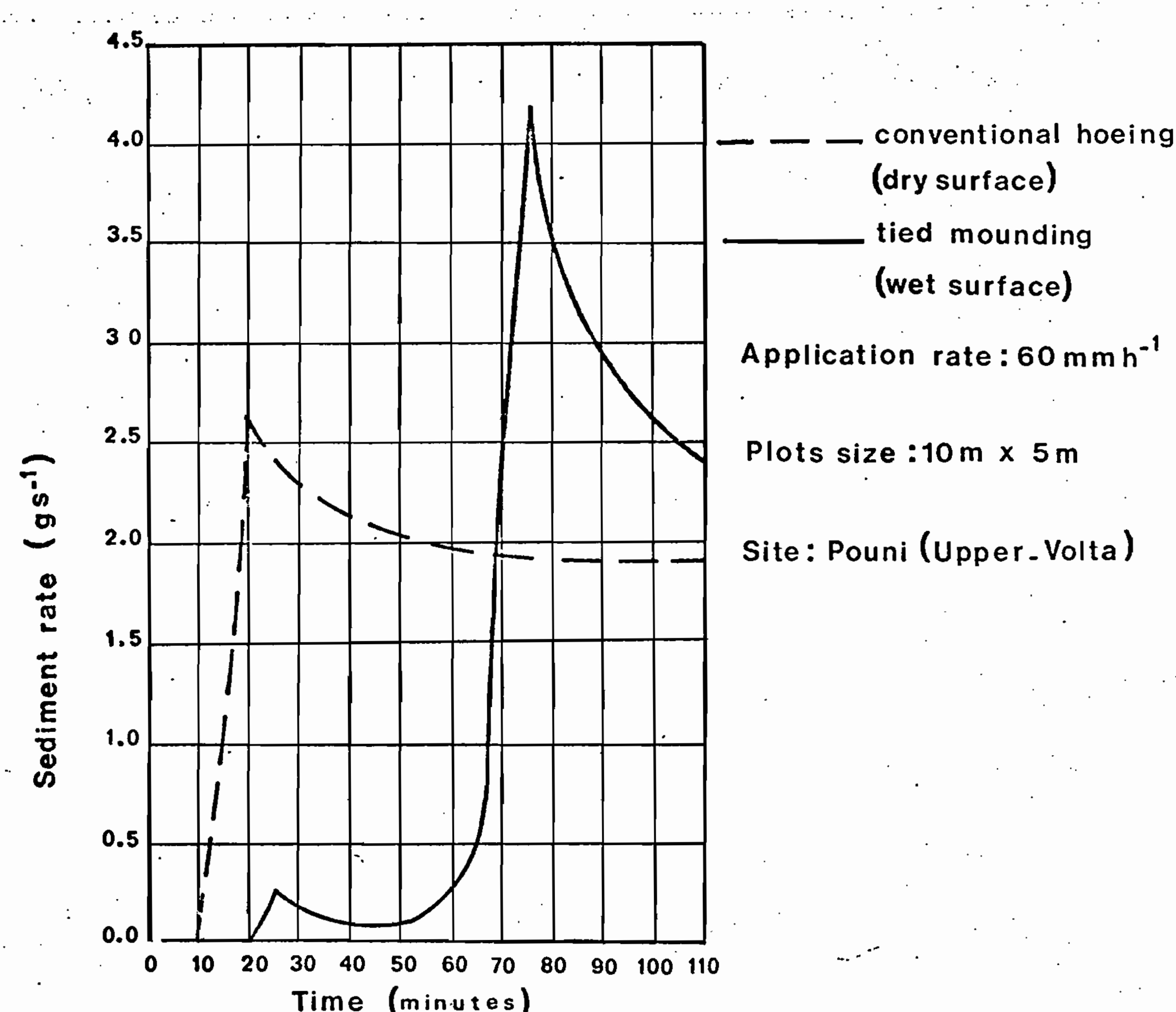

FIG.3 Sedigraphs from conventionally hoed plot and from tied mounded plot

<u>Plant residue mulches</u> Large variations are observed among the values of the erosion reduction factor C (table 6). They cannot be ascribed to the types of mulch since the percentages of surface cover were the same in all cases: 100%. But they can result from the differences between the

ground materials underneath. As a matter of fact, mulching is more effective for sandy soils, namely for soils which are the most susceptible to splash erosion (Ekern 1956, Mazurak & Mosher 1968). In the opposite, where slaking occurs even without any effect of rainfall impact as for vertic soils (Valentin 1981), the efficiency of mulch cover is more restricted. Therefore, mulching should not be used regardless the properties of the topsoil.

Table 6 Combined surface texture and mulch effects on factor C

Location	soil unit (F.A.O.)	textural class (U.S.D.A.)	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

CONCLUSION

Field studies using rainfall simulation can supply pertinent information regarding erosion measurement and control, provided few rules are respected:

(a) experimental procedure is adapted to climatic conditions,

(b) tests are conducted on appropriate plots: for example, 1 m^2 plots are not adequate to asses the effect of conservative practices.

The results on erosion control suggest that caution is required when deriving local C and P values to completely different situations. The 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 therefore considered as hazardous. As a result further information about interactions of erosion factors is needed. It would require more works on erosion processes.

Ruiz Figueroa, J.F., (1983) Les micro-organisations pelliculaires superficielles formées sous pluie simulée sur des sols ferrallitiques de savane (Centre Nord de la Côte d'Ivoire). Doct.Ingr. thesis, Instit.Nation.Agron. Paris-Grignon, Paris.

Swanson, N.P., (1965) Rotating-boom rainfall simulator. Tr. of the A.S.A.E. 8(1): 71-72.

Valentin, C., (1978) Problèmes méthodologiques de la simulation de pluies. In: Erosion agricole des sols en milieu tempéré non méditerranéen (Proc. Strasbourg Symp.20-23 Sept. 1978), 117-122, Strasbourg Univ.-INRA.

Valentin, C., (1981) Organisations pelliculaires superficielles de quelques sols de région subdésertique (Agadez-Niger). Dynamique de formation et conséquences sur l'économie en eau. Doct.3°cycle thesis, Paris 7 Univ., France.

Wischmeier, W.H., & Smith, D.D., (1958) Rainfall energy and its relationship to soil loss. Trans. AGU 39(2):285-291.

Wischmeier, W.H., & Smith, D.D., (1960) A universal soil-loss estimating equation to guide conservation farm planning. 7th Intern.Congr. Soil Sci. vol.I:418-425.

Wischmeier, W.H., & Smith, D.D., (1978) Predicting rainfall erosion losses. A guide to conservation planning. Agric. Handbook N°282. Washington, D.C., U.S.A..