

SOIL EROSION IN THE SAHELIAN ZONE OF AFRICA: ITS CONTROL
AND ITS EFFECT ON AGRICULTURAL PRODUCTION¹

R. Fauck²

SUMMARY

Those features particular to Sahelian soils which determine erodibility are discussed. Mean wind and water sensitivity are given for the major categories of Sahelian soils in three classifications. Qualitative and quantitative data for forms and degrees of erosion are given as determined by various methods (runoff plots, rain simulator). They are complemented by theoretical evaluations using the Fournier and Wischmeier formulae. The values for the R, K, C, and P terms of the Wischmeier equation give a good estimation of the average soil losses in various situations comparative to data obtained in the USA and show the strong erosive potential of rainfall in semi-arid regions.

The effects of erosion on crop yields and on the productivity of pasture land are analyzed. The distinction is made between the effects of runoff and those of erosion. Runoff decreases infiltration, modifies the soil water balance and increases aridity. Loss in potential soil fertility is caused by the decrease in water available in the soil, by the shortening of the growth period, and by soil losses caused by water and wind erosion.

Wind erosion control must involve restricting overgrazing, which is a socio-economic and political problem as much as a technical one. Setting aside protected areas is a very effective practice, but it is of limited use. Surface tillage practices prove effective in the regeneration of certain grazing lands.

The C factor is the most important term in the Wischmeier equation. With the exception of the most basic ones using stones, mechanical practices (contour plowing) are not suitable in the Sahel zone.

All soil tillage practices have increased infiltration as their basic goal. Biologic methods (crop residues, mulching combined with

¹ Contribution from Office de la Recherche Scientifique et Technique Outre-Mer, Paris.

² Inspecteur Général de l'ORSTOM, Office de la Recherche Scientifique et Technique Outre-Mer, Paris.

undisturbed residues of volunteer vegetation) control erosion most effectively.

The conclusions concern the need to promote the integrated management of the Sahelian region on ecological bases -- erosion problems being but one aspect of a balanced ecosystem. This management must be adapted to the specific conditions of the very diverse Sahelian region, and they must deal with the probability of future periods of exceptional dryness.

GENERALIZATIONS

The Sahelian region is situated between the desert zone and the Sudanian zone in Africa south of the Sahara. The northern and southern boundaries are only approximate because the area constantly changes. Besides there are many varying geographic definitions of the Sahel. It is the climatic characterization which is of interest here. This is a region where a 2-4 month monsoon rainy season alternates with a long 8-10 month dry season. The annual potential evapotranspiration of more than 2 meters always exceeds the rainfall. The isohyet limits are 100 mm and 650-750 mm -- but these values are very theoretical when the irregularity of the rainfall is considered not just in time, but also in space (Rijks, 1971). Moreover, there are few meteorologic stations and the determination of the isohyets is only approximate. Some distinguish two sub-regions, the Sahel of the nomads between 250 and 650 or 700 mm depending on the country. This geographic zone represents a band that crosses northern Senegal, Mauritania, central Mali, northernmost Upper Volta, Niger, Chad, northern Cameroon, northern and central Sudan, and some parts of Ethiopia and Somalia. The Cape Verde Islands and eastern Gambia should be included in this list. In many of these countries the official boundary of the Sahel is often set back to 800 mm and even 850 mm average annual rainfall.

The word "Sahel" actually corresponds to very variable ecosystems: from islands to extremely inland countries, with or without major river systems, located on sedimentary or crystalline geologic rocks sometimes involving very diverse soils, and the concept of the isohyet proves to be an inadequate way to characterize its boundaries. Aridity is the only thing common to all the ecosystems.

Between 1968 and 1973 these countries underwent a period of exceptional dryness. The rainfall was 20-50% below average. This substantial increase in aridity had social and economic, as well as biologic consequences (Bille, 1974). The impact of the drought was also apparent in soil fertility and particularly showed up in an increase in erosion. The initial cause was the serious modification in the density

of plant cover caused by the decreased water supply. Overgrazing of the herbaceous ground cover and shrubs increased the destruction of the plant cover. It is often hunger and not thirst that has caused the high mortality rate in cows, sheep and goats. Besides stripping the soil by overgrazing, excessive trampling due to the concentration of herds around water sources, wells, temporary ponds or permanent waterholes caused degradation of the structure of the upper horizons of certain soils. These soils have, then, become very vulnerable not only to wind erosion but also to erosion caused by runoff.

After each dry season, the rains, no matter how many, always fall at the beginning of the rainy season in the form of tornadoes with high intensities. Falling on land without plant cover, with a surface horizon disturbed by overgrazing or trampling, these rains cause intense runoff reaching erosive intensity in many places and causing substantial soil loss. Later, during the new dry season, wind can carry off the finest soil particles because the vegetation no longer creates an obstacle and the soils have lost their surface cohesiveness.

In these circumstances the combined effects of wind and runoff erosion (which are normally processes affecting different kinds of soils) have, in certain cases, and on the same soils, caused substantial damage.

Much information on the effects of drought has been disseminated throughout the world and the term "desertification" has been used (Boudet, 1972; CTFT, 1973; Le Houerou, 1973; Monod, 1973). The United Nations organized a general conference with "desertification" as its theme which took place in August 1977 in Nairobi. The FAO and UNESCO have been entrusted with the creation of a world map of small scale desertification.

This paper will be limited to an attempt to evaluate the present state of our knowledge of the risks of erosion in the Sahel. These risks are dependent on climatic data, on topographic conditions, but also on the particular characteristics of the soils. The role of these characteristics will be examined first and the discussion will be limited only to those groups of soils used for rainfed cultivation. In practice it is these groups which are most affected by the erosive phenomena.

THE GENERAL CHARACTERISTICS OF SAHELIAN SOILS WHICH DETERMINE THEIR ERODIBILITY

"Climatic aridity" distinguishes the morphology of the Sahelian soils and gives them a certain number of common characteristics (Aubert, 1961; Berry, 1974). The characteristics of non-flooded or waterlogged soil types are less depth, often large amounts of sand,

very evolved but insufficient organic matter, poorly developed structure to weak stability, relatively high rate of saturation in bases, soluble elements either concentrated on the surface or at a slight depth (Dabin, Fauck and Pias, 1967). A water regime characterized by an annual potential evapotranspiration greater than the total rainfall and high temperatures with important surface variations must be included in the list. The hydrologic balances vary though according to the soil's topographic position and morphologic characteristics.

The various classifications or legends having a worldwide scope use these various common characteristics to define their upper levels. Thus in the FAO legends the yermosols, xerosols, regosols, and arenosols are distinguished by the combination of the following criteria: water regime, ochric horizon, presence or lack of cambic, argillic, calcic, gypsic horizons. These are the same basic criteria which are used in Soil Taxonomy (aridisols, torr and ust suborders, ochric groups, lithic sub-groups etc., Dregne, 1976). The two systems of utilization of the particular sandy texture which gives soils their specific natures (arenosols, psamments) need to be added. The current French classification relies on the concept of evolution in relation to the mother rock (raw mineral soils, slightly evolved soils), on ionic dominance (calcomagnesimorphic soils), on the distribution of organic matter and the rate of saturation of their complex (isohumic soils). The sub-classes are defined either by climatic data or granulometric data (lithosols and regosols). The three systems, though, are in harmony when it comes to the use and definition of the term "vertisol" at the upper level of each of the classifications.

However, when it is a question of susceptibility to water or wind erosion, none of the legends or classifications, at least on the upper levels used in the case of small scale maps, give any certain way of defining erodibility. The characteristics which determine this erodibility are:

- the texture of the surface horizon: the amount of sand with varying granulometry (for wind erosion), amount of colloids (for runoff);
- the quality of the surface structure, in particular the amount of aggregates smaller than 0.84 mm., the stability of this structure with an idea of their resistance to degradation caused by trampling by the herds or the passage of machines, and especially the tendency to form a fine surface crust with a loss of porosity. The quality of the structure is also determined by the presence of certain ions (sodium) on the complex. In certain cases algae and micro-organisms have modified the surface structure (biological deposits).
- the permeability of the upper horizon which is conditioned by the texture and the structure, and especially the evolution of speed of permeability in time (rate of runoff).

- amount and forms of calcium carbonates. They affect the structure and permeability, but their calcic rocks are very rare in the Sahel.
- the clay's mineralogic type: the 1/1 clays generally give unstable structures in the semi-arid climates, the 2/1 clays, because they can swell, often lead to gullyng. To simplify things, the characteristics used in the upper levels of the classifications only permit the evaluation of certain aspects of the theoretic risk of erosion by using major textural distinctions like psamments, regosols, lithosols. But in practice erodibility can only be safely defined at classification levels which permit better determination of the textural classes and the quality of the structure of the surface horizon. This most often occurs at the level of the family (Soil Taxonomy, French classification). With the FAO legend (1976) the use of "phases" means improvement. The phases are subdivisions of soil units based on characteristics which are important in land use or management but which have no diagnostic value when it comes to the separation of the soil units themselves. Moreover, the definition of these phases corresponds to those formulated in Soil Taxonomy, but they have the advantage of being shown on small scale maps (1/5 million, FAO, UNESCO, 1974).

Table No. 1 gives a qualitative evaluation of the erodibility of the main Sahelian soils with an attempt made to correlate the three classifications and to name the soils. It is based on the interpretation of data supplied by pedologic studies done in the Sahel (Audry and Rossetti, 1962; Gavaud, 1968; Dabin, 1969; Boulet et al., 1971). The descriptions and the analyses available allow definition of the most common textural classes and determination of the clayey minerals. Generally speaking the kaolinitic clays are mainly found in the sandy or sandy-clayey soils which have developed on aeolian drift, on ancient sedimentary rocks, on alluvial material. The presence of type 2/1 clays is almost completely limited to the cases of soils on recent alterations of granitic or basic metamorphic rocks and on ancient, often indurated alterations marked by more humid paleoclimates (Fauck 1967).

Observations by soil scientists also show the structural characteristics specific to certain kinds of widely distributed soils. Thus the alkalinized subarid brown soils and the tropical ferruginous soils (French classification) have a definite tendency to seal at the beginning of the dry season. With the brown soils having a sandy-clayey texture it was found that the profile stayed dry in depth during part of the rainy season. This shows that the relative impermeability of the two upper centimeters limited infiltration (shays decrease of hydraulic conductivities) and caused the runoff of most of the high intensity rains at the beginning of the rainy season. In this case, then, the

TABLE 1. The Erosiveness of the Main Sahelian Soils (Rainfed Agriculture)

French Classification	Soil Taxonomy	FAO Legend	Wind Erosion	Water Erosion	Comments
Raw mineral soils	lithic sub-groups of many orders	lithosols	slight	slight	high run off
-lithosols	orthents or psamments	regosols	variable	slight	depends on texture
-regosols					
Slightly evolved soils	aridisols	xerosols & yermosols	high	slight	sheet erosion
-sub-desert grays					
-lithic soils	lithic sub-groups entisols	lithosols	slight	average	in gullies
-regosolic soils	(torripsamments & torriorthents) aridisols (calciorthids)	regosols (eutric & dystric)	high	slight-average	depends on texture
Vertisols	vertisols	vertisols			
-topomorphe	-chromusterts	-chromic	slight	slight-average	gully erosion
-lithomorphe	pellusterts	-pellic		depending on the quality & size of structure	
Calcomagnesi-morphic soils	inceptisols	cambisol	slight	high	not very scattered soils
-(calcareous browns)	(xerochrepts)	(calcic)			
Isohumic soils	aridisols	xerosols	average-high	slight-average	sheet erosion
-subarid browns	camborthids	haplic			
-red-browns					
-pseudogley browns	haplargids		slight	average-high	frequent gullying
Tropical ferruginous soils					
-unleached	torripsamments	arenosols	slight	slight-average	
-leached to concretions	alfisols (haplustalfs, paleustalfs, rhodustalfs)	luvisols (ferric gleyic)	slight	average-high sheet erosion	sensitivity depends on destruction of the surface crust
Halomorphe soils	nadurargids	solonetz	slight	average	frequent gullying
-solonetz	natrargids				
solodises					

rain available for the soil only represented a fraction of the total rain, the soils actually having a drier pedoclimate than the meteorologic data had indicated in themselves. Note that surface impermeability has another consequence; it blocks the capillary and limits losses through evaporation (mulching effect), which is sometimes an advantage.

The tendency toward surface crusting also affects the halomorphic soils developed on granite calcic-alkaline rocks (solidized solonetz). These soils are of little use in agriculture but they are distributed on long glacis which undergo intense runoff in the beginning of the rainy season and, lower down, gullies can occur in places and even tunnel erosion (piping). Soil erodibility, then, cannot be disassociated from the topographic position of the profiles. But Sahel reliefs vary. The principal types are:

- active dunes and flat-topped hills.
- long glacis with slight slopes, either from erosion or accumulation.
- interdunal plains, more or less covered with sand.
- uneroded, indurated hills and reliefs with outcrops.
- valleys and depressions liable to flooding.

The dunes seem to be the most sensitive to alteration but it is impossible to determine the role of current processes. The present dunal forms in the Sahel are the result of at least three arid climatic episodes in the quaternary age (Leprun, 1971). The soils have different morphological characteristics in each of these dunal systems. The oldest have structural and even textural B horizons. The extent of the alterations becomes apparent when the transition between the upper horizons and the generally reddened structural B horizons is examined. One finds that on most of the slopes and the lower part of the dunes these transitions are the result of the B's having been scraped by erosion then covered by moving sands. With degradation by overgrazing (which is not the only case of superficial alteration) it is this sandy upper horizon which moves on, appearing in places on the surface of the B horizons. It is probably wind erosion which was the active factor in this phenomenon, which is often marked by barren strips, the shrubby steppe having been eliminated here.

The number of modern pottery fragments that can be found in the profiles between 40 and 70 cm. shows that numerous alterations date from the most recent centuries of human occupation. The instances of dunal movement around semi-permanent ponds confirm the instability of this Sahelian environment. Gullies have even been found in the lower part of the dunes. These are probably related to the slightly more clayey soil texture found there. On the other hand, it must be pointed out that these are also the dunal fields which show the most rapid regrowth of vegetation.

The glacis are made up of cycles of quaternary erosion and they are the current sites of substantial runoff and, therefore sheet erosion also, but this is hard to evaluate quantitatively. Recent rills are to be found on the accumulation glacis.

All these observations, both those on the soil's morphologic characteristics and those on geomorphology, show the importance of the risk of erosion in the Sahel. But they do not help in the separation of the ancient processes from the current ones, or in determining the intensity of these current processes. The importance of the paleoclimatic histories though indicates that the Sahel soil cover is partially out of balance in relation to current climatic conditions. This unbalance explains the instability of the ecosystems and is one of the reasons erosion is as serious a problem as it is.

QUANTITATIVE EVALUATION OF ERODIBILITY

The morphologic study of the soil profiles, even when complemented by analytic determination does not give any way of quantifying erodibility. Attempts to link erosion and the soil's structural stability in the Central African Republic (Quantin and Combeau, 1962) should be brought to mind though.

Two kinds of quantitative evaluations have been done in Africa, the in situ measurement of runoff and water erosion, and theoretic evaluation using preestablished formulae. All the measurements done in the field up until now involve water erosion. Quantification of wind erosion has only just been undertaken within the framework of an experiment being set up in Niger, complementing certain recent observations (Mainguet and Callot, Guy, 1974; Chamard and Courel, 1975).

1) Experiments with runoff plots.

The results obtained up until now relate to Upper Volta and Niger. For comparison, those obtained in Séfa, Senegal (Table 2) can be included -- that is in a Sudanian zone -- but with a single rainy season like in the Sahel. Those obtained in the Ivory Coast (two rainy seasons) are presented in Table 3. In Upper Volta the experiments done at Saria are at the southern limit of the Sahelo-Sudanian zone (850 mm. rainfall). The measurements were done on the various sized plots (200-5,000 m²) on slight slopes (.8%) characteristic of the relief of the Mossi plateau (Roose, 1972). They had been preceded by preliminary studies (Christoi, 1966). The runoff rates are slight in the natural milieu, that is in very open wooded savanna. They vary between 2 and 32% depending on the type of cultivation (Roose, 1972), -- bare soil (control) undergoing

Table 2. Summary of the Annual Results Obtained on Erosion Field Plots in SEFA (1960-62) (Roose, 1967)

No. Plots	1	2	3	4	5	6	7	8	
1960	Crops	peanut	peanut	peanut/sorghum	peanut	peanut	rice	peanut	peanut
	Mode	tradit.	dech.	dech/E.V. S.C.	dech.	dech.	dech.	dech.	tradit.
	P	1171	-	1302	-	-	-	-	-
	R mm	220,3	430,5	227,6	328,3	376,3	398,1	375,5	352,4
	R %	18,8	36,8	17,5	25,2	28,9	30,6	28,8	27,1
	E t/ha	5,35	12,15	4,52	3,59	6,99	7,38	6,98	7,30
	Rt kg/ha	1900	2850	2580	2660	2640	400	2120	2580
1961	Crops	rice	rice	rice/peanut	rice	rice	peanut	Sorg/E.V.	fallow
	Mode	tradit.	dech.	S.C. dech.	dech.	dech.	dech.	dech.	tradit.
	P	1231	-	1185	-	-	-	-	-
	R mm	461,1	617,4	374,3	446,8	431,0	470,0	414,4	157,3
	R %	37,5	50,2	31,6	37,7	36,4	39,7	35,0	13,3
	E t/ha	29,95	54,48	8,05	6,79	10,84	5,24	8,65	9,78
	Rt kg/ha	neant	neant	534/1940	1184	872	1720	46.000	-
1962	Crops	peanut	cotton	sorg/grain	sorg/E.V.	peanut	cotton	fallow	fallow
	Mode	tradit.	dech.	dech.	dech.	dech.	dech.	dech.	tradit.
	P	1084	-	1223	-	-	-	-	-
	R mm	247,3	462,8	513,9	296,2	474,3	402,9	180,9	228,3
	R %	22,8	42,7	42,0	24,2	38,8	32,9	14,8	18,7
	E t/ha	2,91	18,52	3,29	1,19	3,32	4,25	1,46	1,85
	Rt kg/ha	1025	266	760	-	2224	460	-	-
<p>P = rain R = run-off E = erosion Rt = crop yield tradit. = traditional dech. = stubble plowing</p>									

Table 3. Erosion and Run off with Various Plant Covers Between Abidjan and Ouagadougou
Erosion Field Plots from 90-5,000 m² (Roose, 1972)

Stations	Erosion tons/ha/year			Run-off % of annual rains			
	Slope	Natural environment	Bare soil	Crop	Natural environment	Bare soil	Crop
ADIOPODOUME (1956-1971) (ORSTOM)							
Secondary evergreen forest 2100 mm : 4 seasons 90-250 m ² plots	4,5 %	-	60-90	-	-	42	-
Climatic erosiveness R _{UA} = 800-1200 (Roose, 1971)	7 % 22 % 63 %	0,03 0,2 1,0	100-170 500-750 -	0,1-90 - -	0,14 0,7 0,7	38 32 -	0,5-20 - -
BOUAKE (1960-1970) (IRAT-ORSTOM)	4 %	0,05-	18-30	0,1-26	0,3	15-30	0,1-26
Dense shrubby savanna 1200 mm : 4 seasons 200-250 m ² plots Erosiveness R _{UA} = 250-500 (Bertrand, 1967)		0,20					
OUAGADOUGOU (1967-1971) (CTFT-ORSTOM-IRAT)	0,8 %	0,05-	10-20	0,6-8	2,5	40-60	2 -32
Clear wooded savanna 850 mm : 2 seasons 200-5,000 m ² plots Climatic erosiveness R _{UA} = 250-450 (CTFT, 1971)		0,15					

40-60% runoff. Taking into consideration the unbalance between the water contributions and the losses through evapotranspiration, one becomes aware of the seriousness of such superficial losses in time. These losses, though, still may have a role in the agro-pastoral economy because part of the water is caught in depressions, in ponds especially, which are undeniably important when it comes to the survival of herds in the dry season. Erosion (i.e., the amount of soil carried off) likewise varies according to the soil treatments. It can be slight under cultivation but can reach 8 tons, while soil losses from bare soil range from 10-20 tons/ha/year equalling 1000-2000 tons/km²/year.

In Niger experimentation was done in the Allakoto experimental station (Maggia Valley - Delwaulle, 1973). Annual average rainfall is around 450 mm, the length of the rainy season not exceeding 4 months. The vegetation is a shrubby savanna greatly affected by man and is currently very sparsely cultivated. It is a plateau cut through with large valleys, on which very diverse soils have developed in connection with the great diversity of geologic rocks. Most of these soils are chemically rich, which is exceptional with respect to the largest part of the Sahel and this is why numerous development programs have been set up there. But the seriousness of the erosion phenomena has already caused serious concern among specialists who have sought not only to quantify the phenomenon but also to seek uncomplicated ways of combatting it which are adapted to the socio-economic conditions of the country.

Four plots have been set up. They are on the order of 4000 m² -- that is, they are comparable to the fields of the Haoussa. They received the following treatments:

- Plot 1: isohypse stone walls and plowing
- Plot 2: control, traditionally cultivated
- Plot 3: contour vegetation rows and plowing
- Plot 4: grassy isohypse stone mounds

The area slopes are 2-5% and the soils come from calcareous rocks. The field plots were planted on 3% slopes and on brown calcareous soils (French classification) which correspond well to the calcicxerosols (FAO) and the camborthids (Soil Taxonomy). The study of the distribution during the time of the rainfall showed that there were maximum intensities each year (during a 5 minute period) greater than 74 mm/h. The annual frequency of these intensities varied from 1 to 14 from 1966-1971.

Runoff only occurred after a certain amount of rain had fallen; this was about 12 mm for the control plot. This value is very theoretical though, and the initiation of runoff not only depends on the rain's intensity, but also on the moisture of the upper horizon. It

also varies depending on whether it is the beginning of the rainy season when the soil is bare, or at the end of the rainy season when there is substantial plant cover. Table 4 gives the average percentages of runoff recorded. A noticeable difference is found between the treatments and the annual average runoff is around 20% during the "normal" years. The simple anti-erosion treatments used here are very effective; the runoff is always less than 9%. The values for erosion, that is for soil carried off by runoff, do not agree with the values for runoff. For 1968, which was a year with slight average rainfall, interesting results were obtained. For the traditionally worked field, erosion was greater than 5 tons per hectare, basically caused by two rains. On the other hand erosion on treated plots remained slight and was always less than 500 kg/ha, erosion less than 7.5 tons/hectare being considered tolerable. This problem of the effectiveness of erosion control methods will be taken up again later on.

Other experiments with runoff plots have been done in the Sudanian regions. Although there is cause for reservation, the results, particularly those at Séfa (Senegal), can be considered indicative of the most southern Sahelian or Sudano-Sahelian regions (Fauck, 1954; Fauck, 1956; Roose, 1967). Other results have been obtained with hydraulic catchment basins but they only relate to the computed runoff rates (Brunet-Moret, 1963; Dubief, 1953; Girard, 1975). These studies show the importance of exceptional flooding in maximum flow and volume. These are floodings whose decrease in outflow is hampered from upstream to downstream in hydrographic networks whose morphology is the product of more humid quaternary climates (Rodier, 1975). These results show the existence of periods of very high rates of runoff for well-drained soils. These are mainly at the beginning of the rainy season. In these conditions the annual average runoff value supplied most often in hydrology does not have any great significance for erosion because, for erosion, it is the particularly wet or dry years which are the most important.

2) Experiments with the rain simulator.

Experiments were done in 1976 near Lake Bam in the Voltaic Sahel. The results are still very high during the first rains which fall on dry soil. They fluctuate, in most cases, between 40 and 50 mm/h for 60 mm/h simulated rains (Collinot, 1977, unpublished). Erosion varies considerably depending on the soil. Identical experiment plans (intensity, length of the rains, same initial state of the plots, similar slopes) have given the following extreme values: soils with surface gravel (natural mulch) 0.02 t/ha/hr; thick sandy soil: 1.7 to 2.9 t/ha/hr.

Table 4. Allokoto, average runoff percentages recorded.

Year	Rainfall	R	P1	P2	P3	P4
1966	487.0	180.4	5.1	18	6.1	*
1967	515.3	305.8	5.9	22.5	5.0	0
1968	354.3	150.8	0.8	8.5	1.2	0.6
1969	506.8	178.0	2.3	21.4	6.8	1.2
1970	469.5	250.9	5.6	19.2	8.5	2.1
1971	289.6	152.6	1.3	10.5	1.3	0.3
Moyenne	437.0	198.5	3.8	17.6	5.2	0.9

* Not used Delwaulle - 1973

Table 5. R value in Upper Volta.

Stations	Year	1966	1967	1968	1969	1970	1971	1972	Average
DORI		440	190	176	491	165	101	262	261
Ouahigouya			390	315	353	225	321	203	301
FADA N'GOURMA		442	526	439	458	302	322	509	428
Ouagadougou			389	252	725	228	414	786	466
SARIA				357	501	389	320	217	357
Mogtiedo				406	467	384	256	378	378
BOBO-DIOULASSO		493	437	664	538	880	421	442	554
FARAKO-BA			365	393	489	736	372	554	485
NIANGOLOKO				707	846	924	314	491	656
GAOUA		419	274	910	644	713	496	310	538

Delwaulle - 1973

3) Theoretic formulae.

The theoretic risk of erosion in the Sahel has been evaluated by different methods. With respect to wind erosion it must be realized that the greatest part of the sandy particles of the dunes are distributed in modes equal to or less than 200 microns and thus are liable to being easily carried off by winds. But real erosion is dependent on the quantity and quality of the aggregates binding these particles. However, examination of current data supplied by wind gauges shows that the average wind velocity is relatively slight (only 15% of the winds have a velocity greater than 5 m/s at Dori (Upper Volta) (Courel, 1977). Evidence of wind processes and the recent evolution of "coudeyrization" (caving in of dunal cavities), though, shows the reality of deflation.

For water erosion it was Fournier (1960 and 1967) who took the first theoretic step using the basic formula p^2/P , p being the rainfall in the wettest month and P the normal rainfall. The figures that were obtained vary around 2,000 t per km^2 per year. This is the figure obtained for bare soil in the runoff experiments in Upper Volta. Right now the FAO is trying to use a formula derived from the Fournier formula to characterize small scale erosiveness. But it is the Wischmeier formula that has been most recently used by all the writers. The erosion prediction equation is as follows (Wischmeier and Smith, 1960; Smith and Wischmeier, 1962; Wischmeier and Mannering, 1969; Wischmeier, 1974):

$$A = R.K.C.SL.P.$$

A = average annual soil losses

R = rainfall and associated runoff

K = inherent susceptibility of the soil to erosion by water

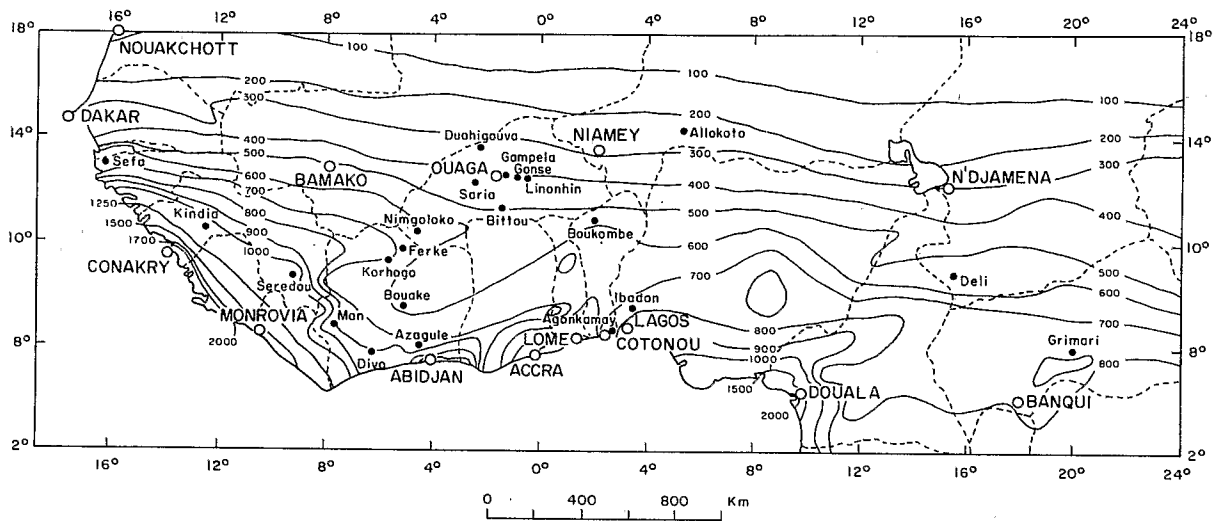
C = cover and management

SL = effects of slope length and steepness

P = supplemental practices

R was calculated for all the experiments -- that is in those cases where complete meteorologic data were available (Galabert and Millogo, 1973; Roose, 1972). In Ouagadougou the R value in 1968 and 1969 was 480 (Roose and Birot, 1970). But for the other years the values varied from 250-450. In Bambey, Senegal the R value was 292 from 1960-1968, for a region with annual rainfall on the order of 600 mm (Charreau and Nicou, 1971). In Niger Delwaille computed R values varying from 150 (in 1968) to 250 (in 1970) and 305 (in 1967) (Figure 1). The annual variation is, then, important, and because of this the examination of series of observations over 20-25 years is necessary in the characterization of the climatic aggressivity of a region, as Wischmeier has done for the entire central American plain. In the Sahel region such series of observations are rarely available, but since there are several pluviometric stations with more than 20 years of data an attempt at resolving the problem was

CHART OF THE DISTRIBUTION OF THE INDEX OF CLIMATIC AGGRESSIVENESS
ANNUAL AVERAGE (R-USA-WISCHMEIER) IN CENTRAL AND WEST AFRICA
SITUATION OF THE EROSION PLOTS



TAKEN FROM PLUVIOMETRIC DATA GATHERED BY THE ORSTOM HYDROLOGIC SERVICE AND
STOPPED IN 1975.
ROOSE (1976)

Figure 1.

made by trying to find a connection between R and the amount of rain. In West Africa Delwaulle suggested adopting a mean formula for the Sahel zone: $R = 0.15884 P^{1.30} - 1.2$ (P 130 being the rain's maximum intensity in 30 minutes). He computed the R values for certain Sahel stations (Table 5). For his part Roose noticed that the ratio between the R index and the rainfall always stays around 0.50 except for the mountainous regions. He drafted a map of erosiveness using 0.45 for the Ivory Coast savanna with 2 rainy seasons, and 0.55 for the savanna and the Sahelian steppe with one rainy season. With this map (Figure 1), R values in the Sahel can be estimated between 100 and 500. But field observations have led me to use these values only with prudence, taking into account the rains' irregularity in time and space in semi-arid regions.

The K factor gives the soil's susceptibility to erosion and it is very important. Various values are currently available. Roose used a simplified method recommended by Wischmeier which used granulometric data, figures for organic matter, structure and permeability. For Upper Volta the K values computed are between 0.23 and 0.27. These figures are for tropical ferruginous soils which have relatively high amounts of fine sand. The soils, then, are not particularly erosion-prone, something which Charreau had already pointed out for Senegal. Consequently the seriousness of the erosion phenomena is basically due to the aggressiveness of the tropical rains and the lack of plant cover.

There is still insufficient data on the influence of the topographic factor, and before drawing any conclusions and making any generalizations the results of current experiments are necessary. The other parameters of the Wischmeier index will be discussed later on.

THE EFFECTS OF EROSION ON PRODUCTION

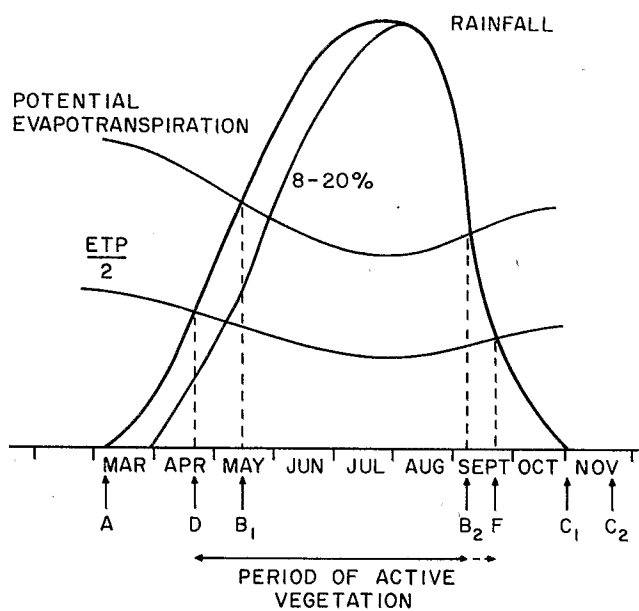
Productivity of pasture land

The problem of pasture land is outside the scope of this study. However, the way dry cultivation and cattle raising complement each other in the Sahel is important and justifies a brief analysis of the matter. It is currently impossible to give any precise evaluation of the impact of erosion on pasture land. There is a great deal of information on the lack of plant cover in connection with erosion, on the modification of the species involved, on the death of forage trees, on the sanding of certain zones, but the various phenomena of soil degradation and fertility loss are difficult to isolate while the spectacular sanding phenomena have a very localized economic impact. However, experience acquired in the other regions indicates that they should not be underestimated (Lyles, 1975; Chepil *et al.*, 1952). What seems to remain is that all the data acquired on the decrease in primary production are usually related to the decrease in available soil water rather than the intensity of erosion.

The yield of rainfed crops

For traditional rainfed crops like millet, peanut, cowpea (*Voandzou subteranea*), cotton, the yields are often very small. But one finds that the two components, runoff and erosion, are equally responsible in lowering fertility. Erosion itself (the carrying off of soil), or its corollary, covering the colluvial deposits or the formation of sandy dunes, represents a usually very localized environmental deterioration, sometimes called desertification. It continues to remain important, even on sandy soils because the peasants prefer to cultivate the dunal slopes. The fertility lost through sheet erosion (the most deceptive) though, or by sand pollution may be underestimated. Besides the impact of salt brought by the wind on the crops is not understood. This salt comes from the saline or alkaline soils of the presahelian regions. Some writers consider this kind of wind pollution important (Boroviskii, 1961; Lyles and Schrandt, 1972), but the effects of runoff, independent of element transfer, may be more important in the semi-arid regions. From it results a decrease in infiltration in unflooded soils and an increase in the unbalance between the actual amount of water brought to the soil and the losses through evapotranspiration, thus increasing environmental aridity. The existence of this water deficit does not adequately explain the decrease in yields. Rainfed agriculture in the Sahel regions is determined by the amount of rain as much as by the length of the useful rains (i.e., those determining the length of the plant cycle) (Cocheme and Franquin, 1967). An "intersections" method was suggested by Franquin (1973). With this method three vegetation periods can be defined by comparing the rain distribution curve with the ETP and ETP/2 curve (Figure 2). Actually the comparison of the ETP curves should be established in time, not with the rainfall curve, but with a curve which represents the water that has actually seeped into the soil. One finds that water lost through runoff, around 20% of the total for example (which seems a common enough figure), significantly displaces the curves of the water balance in time in relation to the ETP and ETP/2 curves which remain constant. This results in a decrease not only in potential reserves in the soil but also in the length of the active growth period. This period has a decisive influence on the average yields of the harvests, even if its effect is relatively indirect. It seems possible to me to conclude that the fight to control erosion must be based on controlling runoff by increasing infiltration. The exact effect of erosion on agricultural production has, though, been measured in certain experimental stations in Upper Volta. The cottonseed yield in Upper Volta has been found to be directly related to the intensity of the soil losses, but also to the evolution of water available in the soils and to the percentage of organic matter. Whether it is in traditional cultivation or in improved cultivation (more demanding), it is water which remains the major factor limiting fertility in semi-arid West Africa (Fauck, 1971) -- damage by water erosion and wind erosion adding to the consequences of water lost by runoff.

DETERMINATION OF THE PERIOD
OF ACTIVE VEGETATION



D-F (or B) : PERIOD OF ACTIVE VEGETATION

A-C₁ : "RAINY" SEASON

D-C₂ : "HUMID" SEASON

D-B₁ : PRE-HUMID PERIOD

B₁-B₂ : HUMID PERIOD

B₂-C₂ : POST-HUMID PERIOD

THE POSITION OF C₂ DEPENDS ON THE AMOUNT OF
WATER STORED IN THE SOIL DURING THE HUMID
PERIOD.

P. Franquin (1973)

Figure 2.

CONTROL METHODS

Wind erosion

Methods of control are known (USDA, 1958; Chepil and Woodruff, 1963) and the advantages and disadvantages of the various techniques (Chepil and Moldenhauer, 1962) are data which can be extrapolated in Africa where one must, however, emphasize the importance of sandy materials coming from the wind in relation to the situation found in the United States. The basic idea is to stop or limit the deterioration of the plant cover (by overgrazing especially), which is the basic cause of susceptibility to wind erosion. This is not a simple technical problem, but one with numerous socio-economic and even political overtones (FAO, 1974; United Nations, 1975). Overgrazing mainly results from the concentration of herds around permanent and semi-permanent water sources and its elimination assumes the adoption of a distribution policy for forage and wells which takes into account both the people's customs and the potential for primary production of the different kinds of pasture land in space and also in time. The effectiveness of reserved lands (Depierre and Gillet, 1971) should also be mentioned, but it must be remembered that this involves techniques which are difficult to employ in the Sahel. They show the power of vegetation taking over once again. Ever since normal rainfall has returned after the exceptional dryness in 1968-1973 hard seeds which had stayed in the soil for many years germinated. A considerable plant cover has developed from this in the most arid regions. These areas, temporarily abandoned by human and animal populations, were somewhat naturally preserved. Practically speaking it seems possible to facilitate the regrowth of herbaceous vegetation by harrowing sandy-clayey soils with less than a 10% slope, but the use of this technique is limited due to economic constraints.

Runoff erosion

The choice of control methods is inspired by the results discussed above. Data supplied by various studies on soil use in the semi-arid regions of Africa (Dabin, 1969) on the effects of mechanization on tropical agriculture (Fauck, 1956; Fauck et al., 1969) and those taken from general studies of tropical regions (FAO, 1967; Hudson, 1971) belong here too.

Roose's (1971) determination of the values for the C factors (plant cover and cultivation methods) and P (anti-erosive practices) in the Wischmeier formula must be included. The C factor is the most important conditional factor. It varies as a function of the plant cover. Setting the savanna on fire, for example, especially if it is late, very appreciably increases the runoff and the amount of solid material.

When the soil is completely bare, runoff may be multiplied by 20 with catastrophic soil losses. For cropped soil, C values are very variable. Roose's figures (1971), valid for the whole of West Africa, but basically established in the Sudanian or Guinean regions, may be cited.

For bare soil, by definition	C = 1
prairie in good condition	C = 0.01
burned or overgrazed prairie	C = 0.1
sorghum, millet	C = 0.4 - 0.9
cotton	C = 0.5 - 0.7
peanut	C = 0.4 - 0.8

In every case erosion basically depends on the percentage of soil not covered by vegetation at the beginning of the monsoon rains.

The P factor represents classic anti-erosion practices. Roose (1972) and Delwaulle (1973) determined the following values:

tie ridging	P = 0.2 - 0.1
strip cropping	P = 0.3 - 0.1
straw mulching (10 t/ha)	P = 0.01
synthetic mulching	P = 0.5 - 0.2
dry stone ridges, plowing and fertilizer	P = 0.1

These diverse results led the writers to make a limited choice among the various methods of controlling erosion -- building broad based terraces. Experience has shown that terracing techniques are delicate to use in the Sahel socio-economic environment and that the terraces made are difficult to maintain. In addition there are scarcely any crops profitable enough to compensate the cost of their construction. Finally, the P factors are less than those found for the United States where $P = 0.75$ for isohypse plowing. Taking this into account, the writers do not recommend building terraces. Delwaulle, however, demonstrated the importance of simple techniques using isohypse dry stone borders. But this is not always possible.

Soil tillage

Plowing and ridging have reduced erosion in most of the experiments. Harrowing, which breaks the superficial crust, improves infiltration, especially for sandy and sandy-clayey soils (Charreau and Nicou, 1971).

On sandy-clayey soils in more humid regions, though, precautions need to be taken practicing surface tillage (Charreau and Fauck, 1970) but if they are taken, plowing distinctly increases the yields of rainfed crops. Delwaulle also found higher erosion during runoff occurring after plowing in Upper Volta. The cultivation method, then, needs to be adapted to the soil type, especially by plowing deeper and by choosing a soil tillage method with minimal plowing under. CIDR at Gorum-Gorum (Upper Volta) used sub-soiling techniques which produced good results, mainly for tree regeneration, and harrowing techniques which accelerated the growth of the plant cover. Among techniques commonly used in other arid regions in the world (USA, Australia) it is the least complex ones and those allowing the best water infiltration that are to be recommended. Also, these practices should be undertaken just before the first rains.

Biologic methods

These use plant action. The plant either protects the soil against the impact of drops of rain (splash) or provides soil cohesion (roots and contributions of organic matter), or mechanically stops runoff. Roose's observations confirm the superiority of biologic methods over mechanical methods (terracing). Whenever it is possible the initiation of vegetation must be facilitated which leads to establishing the importance of early and dense sowing, spreading fertilizer, phytosanitary control and finally the use of improved varieties with a rapid growth rate. Stopping runoff will result in an improvement of the water balance and, correlatively, in better vegetation, better erosion protection, and, finally, higher yields. The use of dead plant cover should also be recommended, for example, if possible, a partial burying of millet and sorghum straw. It should be noted though that cereal stems are often used for domestic purposes (kitchen, fences, roofing) and they are rapidly eaten by cattle or destroyed by termites. These observations lead one to recommend the study of technical solutions adapted to the local socio-economic conditions. In the most Sahelian regions the millet crops are reserved for the dunal sandy soils, pasture land also being soils with shallow glaxis or clay. The erosion phenomena do not have the same importance for these two major soil categories and the previously cited technical solutions must be chosen, taking into account the whole natural and human environment as any modification of runoff on the glaxis could disturb the balance of the neighboring sectors. This means that Sahel management must be done on the basis of ecological data (UNESCO-MAB, 1974). Practically speaking, we need to develop an integrated agriculture/cattle-raising system stemming from a basic principle, improvement of the seepage of runoff waters into the soils, at least into those which can accept them.

CONCLUSIONS

Our current knowledge of the Sahel soil erosion shows the aggressive-ness of the rains, the Wischmeier R coefficient varying from 250-500 which is comparable to the southeastern United States where the "iso-erodents" only exceed 500 in certain areas. Other studies, though, indicate that this coefficient is much higher in Sudanian regions and that it exceeds 1,200 in the lower Ivory Coast. The K coefficient varies from 0.23-0.27 and the soil's susceptibility to erosion is, then, average. This coefficient varies in the United States from 0.03 to 0.60.

There are, however, many gaps in our knowledge. We only have an imperfect understanding of the wind's erosive power and the K values have only been determined for some soil types. Besides the soil water dynamic has only been the object of local or qualitative studies. However, it may be concluded that the principle basic to any anti-erosion management must be the increase of infiltration into the soils. The techniques are known and the simplest are usually the most effective. To apply them, though, we must go beyond the limits of simple erosion problems. An integrated management is needed which takes into account the diversity of the environment resulting from the wide range of soil types and geomorphologic situations. The Sahel represents very diverse ecosystems which have one common dominant factor: aridity, and one fact: unstable balances. It would be dangerous to stop erosion by causing the infiltration of all the runoff waters if that meant the drying up of semi-permanent ponds whose existence determines the pastoral life and the nomadism. Besides, any anti-erosion method which does not take into account the local socio-economic context would be doomed to failure. It could even result in a local aggravation of erosion danger, not to mention the effects on health that could come from the dissemination of certain diseases transmitted by water (bilharziose etc.).

In fact, erosion is but one aspect of a many-sided breakdown in balance. All its aspects must be considered. Breakdown in equilibrium may not only be caused by human activity in relation to the population increase but also comes from climatic risks. These risks are unforeseeable and unavoidable and the possibility of the return of periods of exceptional dryness must be recognized. After these periods "normal" rains will cause great erosion damage because of the degraded state of plant cover. Any ecosystem development project must, then, provide for these climatic risks. Use of the Wischmeier erosion prediction equation (determined by the results expected from current studies) can supply the basic data to correctly define these managements within the framework of an integrated development, but the evaluation of the erosion risk is generally based on the average climatic data over 20-25 years. To perfect the management it may be necessary not only to use this "normal" mean, but also the theoretic values computed from data taken during exceptional years.

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