EFFECTS OF KINETIC ENERGY AND WATER APPLICATION RATE ON THE DEVELOPMENT OF CRUSTS IN A FINE SANDY LOAM SOIL USING SPRINKLING IRRIGATION AND RAINFALL SIMULATION.

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RESUME

Afin d'apporter des précisions sur le rôle de certains facteurs dans les processus de réorganisations superficielles, une expérimentation de terrain a été entreprise sur un sol ferrallitique du centre de la Côte d'Ivoire, mettant en oeuvre irrigation par aspersion et simulation de pluie. L'étude de 65 lames minces a révélé la succession de plusieurs stades de réorganisation. Ces modifications morphologiques de la surface du sol ont été reliées à des mesures hydrodynamiques. Il apparaît que les croûtes structurales résultent d'une désagrégation induite par l'humectation. Les croûtes de dépôt se mettent en place lorsque la conductivité hydraulique saturée des organisations pelliculaires devient inférieure à l'intensité d'apport d'eau. Ce seuil d'intensité est étroitement lié à l'énergie cinétique des gouttes. En revanche, aucune différence significative entre techniques culturales n'a pu être mise en évidence. Parmi les trois modèles d'asperseur utilisés, un seul produit des énergies cinétiques correspondant à des pluies naturelles de faible intensité.

KEY-WORDS :
Surface crusting – Sprinkling irrigation – Rainfall simulation – Kinetic energy of drops – Micromorphology.

INTRODUCTION

Water dropped on crusted soil, whether under irrigation or rainfall, usually infiltrates slowly. Likewise, seedling emergence is inhibited greatly by the occurrence of surface soil crusts, especially for crops grown from small seeds. A number of researchers have used light microscopy (EVANS and BUOL, 1968) or more recently scanning electron microscopy (CHEN et al., 1980) to study the structure of surface crusts and the mechanism of their formation. Much attention was paid on the effect of rainfall on sealing processes by those who have used rainfall simulation (EPSTEIN and GRANT, 1973; VALENTIN, 1981). The influence of surface roughness and cloddiness on the development of seals and subsequent erosion has also been studied (MOLDENHAUER and KEMPER, 1969; JOHNSON, MANNERING and MOLDENHAUER, 1979; BOIFFIN, 1984). However, work on the morphology of crusts formed under irrigation remains scarce (BISHAY and STOOPS, 1975) and little information about their hydraulic properties is yet available. The overall objective of this study was to achieve a better understanding of the processes of crust formation in a very unstable soil. The specific objectives were : 1) to describe the stages leading to crust formation under field conditions, using sprinkling irrigation and rainfall simulation, in combination with micromorphological analysis ; 2) to relate the changes in surface structure to decreasing rates of water intake ; 3) to study the influence of kinetic energy, application rates and the amounts of cover and cloddiness on the crusting processes ; and 4) to propose realistic solutions to avoid crusting in this soil type.

SITE, MATERIALS AND METHODS

The soil

The experiment was carried out at a state-run, mechanized farm in Marabadiassa (central Ivory Coast) where the production of vegetables is seriously hampered by surface crusting. Some characteristics of this sandy loam, developed on shale, are reported in Table 1. A general description of this soil, identified as an Ochric Ferralsol (FAO terminology) and the physiographic region in which it occurs is given by RUIZ-FIGUEROA (1983).

Experimental set-up

The experimental variables studied under sprinkling irrigation were the factorial combination of 3 types of tillage, 3 types of sprinklers and 2 types of surface managements, thus requiring

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Horizon	depth (cm)	clay (%)	fine silt (%)	coarse silt (%)	fine sand (%)	coarse sand (%)	coarse fraction (%)	S.I.I.*	organic matter (%)	pH H_2O
Ap	0-20	18.6	5.6	16.3	41.9	13.9	1.5	4.7	1.6	6.3
B_{11}	20-40	25.4	6.8	13.0	36.2	15.4	0.4	2.4	1.0	5.2
B_2	40-60	27.6	7.0	12.3	30.3	19.1	51.5	2.4	-	6.5
C	60-110	26.9	8.5	8.9	23.2	28.3	71.2	2.0	-	6.1

* : *Structural Instability Index after HENIN et al. (1955).*

Table 1 – Some characteristics of the studied soil.

Type	A	B	C
Number of sprinkler heads	1	1	2
Expected intensity (mm h^{-1})	5	10	15

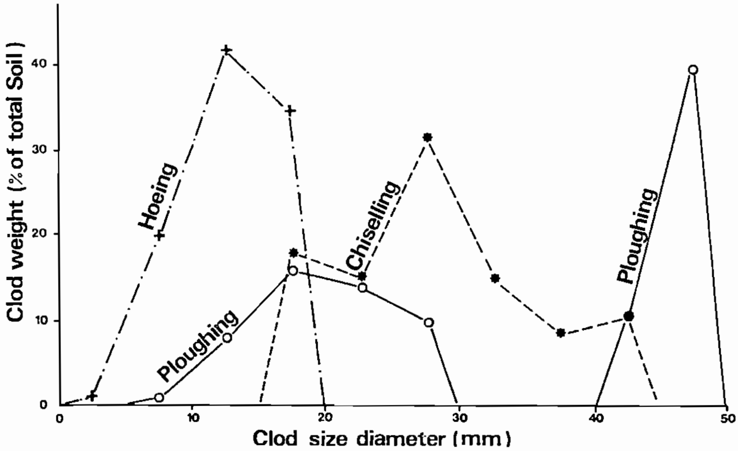
Table 2 – Main characteristics of the tested sprinklers.

	Irrigation			Rainfall simulation			
	Sprinkler type			Surface conditions			
	A	B	C	Shading	Mosquito	Bare	Bare
Measured intensity (mm h^{-1})	6	9	6	120	121	30	123
Kinetic energy (J $mm^{-1}m^{-2}$)	7	16	17	2	3	15	23
Critical rate (mm h^{-1})	>A*	7	6	24	22	8	2

*: *above the application rate.*
The kinetic energy of natural rainfall at 30 and 120 mm h^{-1} are 18 and 23 J $mm^{-1}m^{-2}$ in Abidjan (VALENTIN, 1981). The critical rate under mulch is 22 mm h^{-1}.

Table 3 – Application rates, kinetic energies and critical application rates for the hoed plots subjected to three types of sprinkler and in bare and shaded conditions to rainfall simulation.

Fig. 1 – Initial clod size distribution of the three tillage treatments.



the layout of 18 plots. Tillages included : 1) ploughing to a depth of 30 cm and disking, 2) chiselling to a depth of 40 cm and disking, 3) conventional hand hoeing of the upper 10 cm. Tillage was performed two hours after wetting. Figure 1 shows the initial clod size distribution for the three treatments determined by sieving. The main characteristics of the three rotary sprinkler systems tested are shown in Table 2. Moreover, two surface conditions were compared : 1) no mulch and 2) sugarcane residue used for mulching at the rate of 4.5 tons ha^{-1} which provided about a 100% surface coverage. In order to study the impact of a wider range of kinetic energies on surface crusting, a field rainfall simulator after the design of ASSELINE and VALENTIN (1978) was used to deliver rain with a natural range of kinetic energies (Tab. 3). Rainfall simulation was applied on six hoed 1–m^2 plots at two constant rates : 30 mm hr^{-1} on two plots, bare and mulched, and 120 mm hr^{-1} on four plots : bare, mulched, covered with mosquito gauze (1.3 mm mesh) and shading gauze (50% shading rate). The gauzes were spread at a height of 25 cm above the target area.

Procedures

The test period started before the rainy season (April–May) so that the first runs were on dry surfaces. The remaining three runs were performed after intervals of 17 hr, 4 hr and 43 hr, respectively, to achieve a wide range of initial moistures. Each plot, subjected to sprinkling irrigation and to rainfall simulation, received the same amount of water, namely 4 x 25 mm. The duration of application depended upon the application rates, and thus varied from 12.5 min at 120 mm hr^{-1} to 5 hr at 5 mm hr^{-1}.

Field measurements

In the case of sprinkling irrigation, the plots were associated with 1 m^2 pans which were used as rain gauges. Runoff samples were periodically collected in order to assess the rate of runoff. For rainfall simulation, sprinkling intensity was measured prior to each run by placing a 1 m^2 pan over the plot, and subsequently adjusted to the required rate. Runoff was collected in a reservoir which was equipped with a very sensitive water–level recorder so that the steady infiltration rate, i.e. the difference between the simulated rainfall application rate and the maximum runof rate, could be accurately measured. Saturated hydraulic conductivity (Ks) of the crust was assessed as the critical application rate, i.e. the rate above which runoff occurred, measured under the wettest initial conditions. The kinetic energies dissipated at the soil surface, including those under the gauzes, were determined using the method described by ASSELINE and VALENTIN (1978).

Micromorphology

One undisturbed control sample was taken from the upper 7 cm of each tillage treatment. In addition one sample was collected from the buffer ring of every plot after each run, except for the mulched plots from which only one sample per plot was taken after the experiment had been completed. As a result, 64 thin sections measuring 3 x 4.5 cm and 18 polished impregnated blocks measuring 4 x 6 cm were prepared. These blocks were studied with a binocular magnifier, whereas micromorphological descriptions were made by observing thin sections, 30 µm thick, with a polarizing microscope, using BREWER's (1964) nomenclature. An assessment of the proportion of the material occupied by macrovoids, namely voids greater than 75 µm was attempted by point–counting of visible voids on a grid which covered microphotographs corresponding to a 6x enlargement. Larger magnification, i.e. 16x, was occasionally used to estimate the mesoporosity (30–75 µm) of compacted materials.

RESULTS

Micromorphology of surface crusts

Seven main types of microlayers were differentiated in the uppermost part of the topsoil. Short descriptions of their micromorphological characteristics are given below.
Type c (from "cloddy") : (Fig. 2–1) Skel–insepic porphyroskelic fabric; macroporosity : 35%; interpedal medium to coarse (2 to 6 mm) interconnected macrovoids; intrapedal very fine macrovoids (vughs 200 µm and craze planes 800 µm in longest dimension). This macropedal material corresponded to the tilled layer prior to the experimentation and was therefore used as reference.
Type s (from "structural crust") : (Fig. 2–2 to 2–5). 5 to 18 mm thick; agglomeroplasmic skel–masepic fabric; macroporosity : 30%; very fine compound packing macrovoids (150 to 400 µm). This microlayer was formed under the residue mulch; however, the material under the gauzes exhibited the same value of macroporosity, voids were smaller (80 to 240 microns).
Type i (from "included") : (Fig. 2–3 and 2–4). O.6 to 0.9 mm thick. Plasma virtually absent, or vosepic intertextic fabric, macroporosity : 34%, very fine macrovesicles (100 to 450 µm), orthovoids, and joint planes (450 µm). In several cases, this microlayer displayed water sorted laminae which are included within microlayers of other types. It mainly occurred on mulched plots

or plots subjected to low application rates.
Type cs (from "compacted structural") : (Fig. 2–3 to 2–5). 0.2 to 6.8 mm thick. Insepic with locally skel–mosepic porphyroskelic fabric. The macroporosity (3%) is restricted to very fine macrovughs (75 to 300 µm) and joint planes (200–300 µm) which are parallel to the surface. It should be noted that this microlayer was found in many thin sections but not in those from mulched and gauzed plots.
Type d (from "depositional") (Fig. 2–2, 2–3 and 2–5). 0.6 to 1.2 mm thick; skel–insepic intertextic fabric; macroporosity : 14%; very fine macrovughs and vesicles (175 to 225 µm). Most often this material encompassed two sorted laminae with rather loose grains in the upper part and more plasma in the lowest part. Since this microlayer occurred on the plots were runoff was observed, it might be considered as depositional in origin.
Type d+ (for thick depositional laminae) : (Fig. 2–4). This microlayer differed from the last mentioned one in that it consisted of numerous fairly–well sorted laminae causing it to be thicker (3.7 to 9.1 mm) and more complex. It had insepic intertextic and porphyroskelic fabric with a macroporosity of 8%. It had very fine macrovesicles (150 to 300 µm) and joint planes (700 µm) roughly parallel to the surface. This material was also found on the plots where runoff occurred.
Type e (from "eroded") : (Fig. 2–5). 0.06 to 0.20 mm thick; skel–insepic porphyroskelic fabric; no macroporosity, mesoporosity : 15%; mesovughs 30 µm. This thin microlayer is mainly composed of dense plasma. It developed on the top of the bare plots subjected to intense runoff and consequent erosion.

This inventory of microlayers was used to discriminate seven main patterns (P) among the thin sections. In this respect, each pattern was characterized by the occurrence of one or several microlayers (Tab. 4). The descriptions of the thin sections are summarized in Table 5 where the most developed pattern observed on each plot has been reported. It is worth emphasizing that the formation of depositional crusts was not necessarily related to the previous development of a compacted microlayer since the d–type microlayer might cover either the cs–type microlayer (namely pattern P21) or the c–type microlayer (namely pattern P20).

Kinetic energy and infiltrability

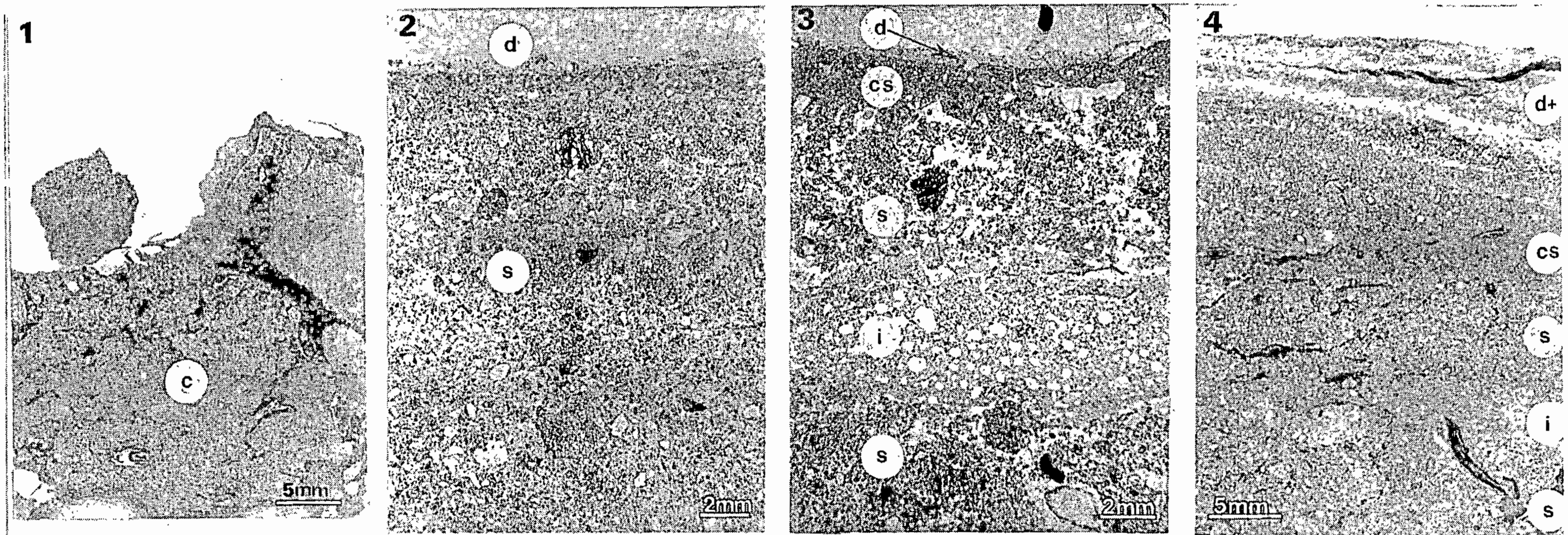
The results on kinetic energy and infiltrability under sprinkling irrigation and rainfall simulation are reported in Table 3. They did not yield any evidence of significant differences among the tillage treatments. It must be added that an analysis of variance applied to the runoff coefficients from the 18 irrigated plots led to the same conclusion. On the other hand, the minimum infiltration rate was found to have been determined mostly by kinetic energy of drops.

DISCUSSION

The influence of wetting, kinetic energy and application rate on the crusting processes

Several stages to describe the crust formation in this soil could be suggested (Fig. 3) as follows :
1) – breakdown and slaking of clods and aggregates due to wetting (P11). This process also occurred where mulch was applied although drops could not impige on the surface directly. This collapse of structure must be attributed to the trapping of air in the most narrow pores during wetting (HENIN et al, 1955). As mentioned by earlier investigators (FARRES, 1978; VALENTIN, 1981), micropedal material then cloggs the macropores resulting in a decreasing infiltration rate (microlayers s and i),
– compaction of the upper layer due to the impact of drops in the bare plots only (P12 associated to the microlayer cs). The considerable reduction of porosity which has been observed , induced a pronounced decrease of the infiltration rate.
2) Deposition of sorted particles by runoff flow on the surface (P21 with cs, P20 without cs). The occurrence of runoff depended upon whether the intake rate, which was related to kinetic energy, was exceeded by the application rate or not. As a result, depositional crusts as described by CHEN et al. (1980), and BOIFFIN (1984), were encountered even on mulched and gauzed plots where this threshold intensity had been exceeded. Where microtopographic variation still existed, low areas in the plots showed thick polygenetic depositional crusts (P22, with d+) whereas higher areas presented a thin and dense plasmic microlayer at the surface (e).
3) The extension of the eroded areas as a consequence of high runoff rates (P3). As indicated by BOIFFIN (1984), wash erosion increases as the surface is smoothed. Consequently, the thin and dense plasmic microlayer expands onto most of the surface. At this stage, the infiltration rate was very low (2 mm h^{-1}).

It appears that crust formation in this soil is primarily induced by wetting. Water drop energy acts to reduce porosity which in turn determines the application rate above which runoff occurs. These critical intensities were related to drop kinetic energies (Fig. 4). The cumulated



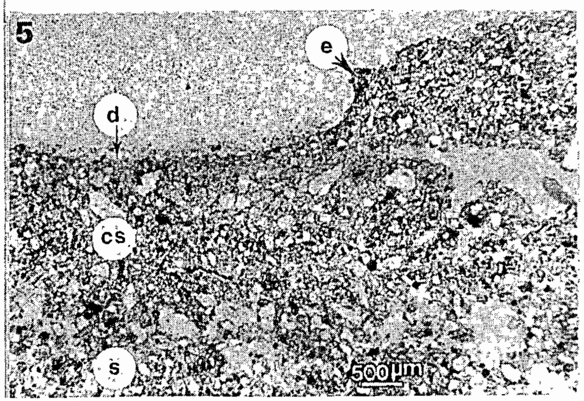
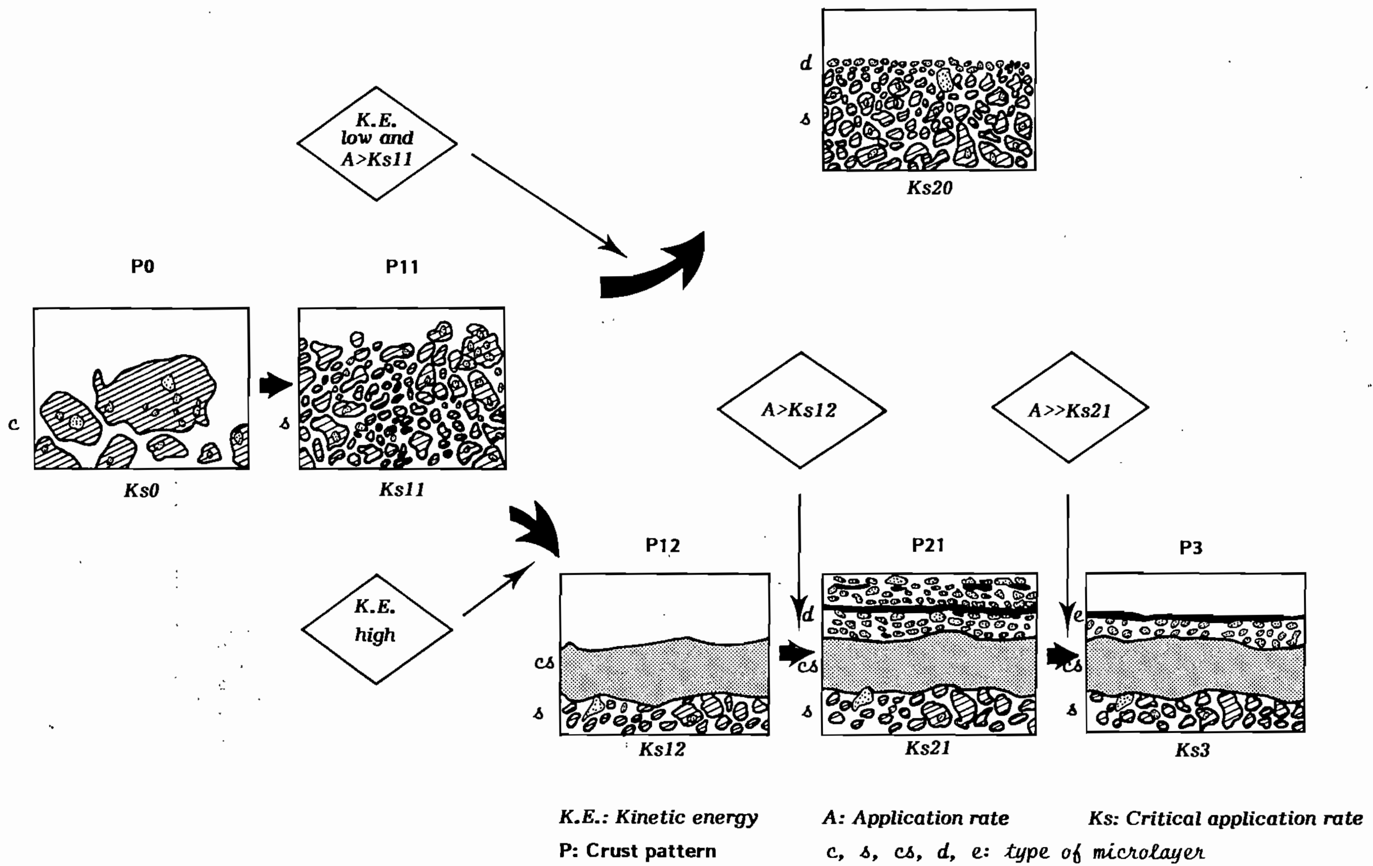


Fig. 2 –
2–1 : Example of pattern P 0. Polished block of the initial structure.
2–2 : Example of pattern P 20. Thin section of a sample from the hoed plot exposed to 120 mm/h simulated rainfall and protected by a shading gauze.
2–3 : Example of pattern P 21. Thin depositional crust from the chiselled and bare plot exposed to sprinkler B after the 4th run.
2–4 : Example of pattern P 22. Polished block of a thick depositional crust from the hoed ans bare plot exposed to sprinkler B after the 4th run.
2–5 : Example of pattern P 3. Erosion crust from the hoed plot exposed to 30 mm/h simulated rainfall, after the second run.

Fig. 3 – Idealized stages of crust formation in the studied soil as related to hydraulic properties.



drop energies with time for type–A sprinkler and type–C sprinkler were similar. But a great difference among the results from both sprinklers was obtained, in terms of morphology and infiltrability. In contrast with the results of MOLDENHAUER and KEMPER (1969), surface compaction and subsequent low water–intake were thus determined by instant kinetic energy, rather than cumulated energy. This result is consistent with those reported by EPSTEIN and GRANT (1973).

Consequences for agricultural practices

Although it has been repeatedly reported (JOHNSON, MANNERING and MOLDENHAUER, 1979 ; BOIFFIN, 1984) that a high proportion of large clods is a favourable condition to control surface crusting, no significant difference among tillage treatments could be found in this study. This may be attributed to the very low water–stability of the material associated with its texture. As far as the use of soil conditioners is still excluded for economic reasons, no realistic solution to enhance structural stability can be proposed . Since wetting induced the breakdown and slaking of clods, a reduction of porosity was observed even under the residue mulch and the gauzes. However, the critical application rates, were much greater on the protected plots than on the plots directly exposed to drop impact. These differences are enough to reduce the runoff considerably. In order to control surface crusting, mulching should be therefore recommended. But further research is still needed to minimize the risk of introducing pests that sometimes accompany mulch applications (VALENTIN and ROOSE, 1980). For that reason, the use of the highly effective shading gauze, as already employed in the vegetable nurseries of this farm, appears to be a better solution. In addition, it must be noted that only one tested sprinkler, type–A, produced impact energy lower than low intensity natural rainfall. Both the others produced storm–like drops and delivered water at a rate which exceeded the hydraulic conductivity of the crusts formed under these high impact energies. As a result, the selection of an adapted sprinkler nozzle is of paramount importance.

CONCLUSIONS

1) The micromorphological analysis leads to a better understanding of the succession of the various stages of the crusting processes and their close interactive relationships with varying hydraulic properties.

2) In this very unstable soil, structural crusts can be formed even when low drop energy is applied.

3) The critical rate above which runoff occurs under very wet initial conditions is strongly related to instant kinetic energy rather than to cumulative energy.

4) A depositional crust is developed when this critical intensity is exceeded by the application rate.

5) For very unstable soils, efficient use of irrigation water can be achieved if the selected sprinklers produce drop energy below the lowest energy of natural rainfall.

	Pattern						
Microlayer	PO	P11	P12	P20	P21	P22	P3
e							X
d+						X	
d				X	X		(x)
cs			X		X	X	(x)
i		(x)	(x)	(x)	(x)	(x)	(x)
s		X	(x)	X	(x)	(x)	(x)
c	X						
	initial structure	structural crusts		depositional crusts			erosion crusts
X : essential microlayer				(x) : associated layer			

Table 4 – Patterns of surface crusts as characterized by the occurrence of typical microlayers.

Cultivation		Surface treatement	Sprinkler type		
			A	B	C
ploughing	sprinkler irrigation	bare	P12	P3	P12
"		mulched	P11	PO	P11
chiselling		bare	P12	P22	P21
"		mulched	P11	P11	P11
hoeing		bare	P11	P22	P22
"		mulched	P11	P11	P11
	rainfal simulation		30 mm h^{-1}	120 mm h^{-1}	
"		bare	P3	P3	
		mulched	P20	P20	
"		shading gauze		P20	
"		mosquito gauze		P20	

Table 5 – The observed crust patterns as related to the experimental conditions.

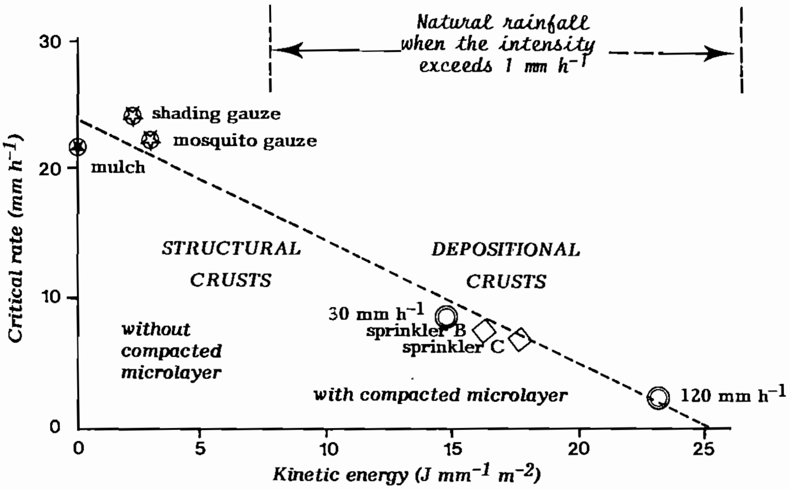


Fig. 4 – Crust and microlayer development under various combinations of kinetic energy and water application rate.

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