Soil Crusting : The African View

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I. Introduction

Although the phenomenon of soil surface crusting has been known for a long time, ITS serious consequences have not been fully appreciated. The influence of soil crusts on soils and eventually on the vegetation and environment is of particular importance in Africa, where extremes in pedologic histories and climates are commonplace. Too often the processes beginning with soil crust formation proceed to water and soil loss through erosion, followed by reduced plant cover and, in the case of cultivated land, reduced yields. This is followed by increased animal and human pressure on the land and in many cases increasing desertification. For economies heavily dependent on a strong agricultural base, the ultimate consequences are severe.

In Africa, soil crusting is serious not only in the drier regions, but over the whole range of climates. In humid areas, denudation results in exposure of the soil surface to the destructive effect of high energy rain. Simultaneously, the loss of soil organic matter is very rapid. In

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these fragile environments the extent of bare soil areas increases, and the sustainability of biomass production is reduced (Wilkinson and Aina, 1976; Roose, 1977; Valentin and Janeau, 1989). The effects on agricultural production and quality of life are obvious.

With an increasing realization of the significance of soil crusting, the phenomenon has been studied very widely in Africa, e.g. in Cameroon (Jacques-Felix, 1950), the Centrafican Republic (Quantin and Combeau, 1962), Egypt (Bishay and Stoops, 1975), the Ivory Coast (Roose, 1977), Kenya (Muchena, 1989), Mali (Leprun, 1978), Mauritania (Audry and Rossetti, 1962), Mozambique (Farres, 1987), Niger (Boulet, 1966), Nigeria (Sombroek and Zonneveld, 1971), Senegal (Aubert and Maignien, 1948), South Africa (Hutson, 1971), Tchad (Bocquier, 1971), Togo (Pleuvret, 1988), Tunisia (Escadafal, 1981), Zambia (Fritsch and Valentin, 1987) and Zimbabwe (Nyamapfene and Hungwe, 1986), mentioning only the earlier studies in each country. Obviously the literature is widely dispersed and not always readily accessible. Therefore, this review should help to correct these deficiencies and summarize the state of the art on soil crusting in Africa. The basic aspects of the phenomenon will not be dealt with in detail since they are very adequately expounded elsewhere (e.g. Carey and Evans, 1974; Callebaut et al., 1985; Shainberg, 1985). Rather, data and findings pertaining to Africa will be presented.

II. Soil Crusts : General Aspects

A. Types

The two main types of soil crusts generally recognized are *structural* and *depositional* crusts (Shainberg, 1985). The former are formed due to the shattering effect of raindrops on an otherwise structurally more stable soil surface, followed by a reorientation of soil particles, while the latter is formed by sedimentation of particles from standing or slowly flowing water. However, detailed field and micromorphological studies have led to a more comprehensive classification (Casenave and Valentin, 1989; Bresson and Valentin, 1990), details of which are given in Table 1 and Figure 1. Although this scheme was developed for the arid and semi-arid zones of west Africa, it also fits crusts described in the arid areas of northern Africa (Escadafal and Fedoroff, 1987) and could be used in the more humid regions as well (Valentin and Janeau, 1989; Poss et al., 1991). In Zimbabwe, Nyamapfene and Hungwe (1986) mapped the areal distribution of crusted soils derived mainly from sediments and metamorphic volcanic rocks. They identified four main types of crusts; both thin and relatively thick multi-layered crusts of high bulk density occur on both sandy and silty soils.

Levy et al. (1988a), in a study of artificially formed crusts (by rainfall simulator), showed that the microtopography of a crusted surface varied considerably. The scale, in respect of area of study, determines whether important features are revealed or not. Thus it was shown that a crusted surface of a Plinthustalf soil from the Transvaal (South Africa) consisted of "plains" and "mounds", which differed significantly. Increasing the soil's ESP from 1.3 to 15.0 resulted in an increase from 77% to 90% of the area occupied by the "plains". The stability of the "mounds" in a crusted area could play an important role in the overall infiltrability. Similar results were reported by Valentin (1991), using image analysis.

Observations by van der Watt and Claassens (1990) on the crusting of a Rhodic Paleustalf from the Makatini Flats in Natal revealed that under continuously moist conditions a very thin

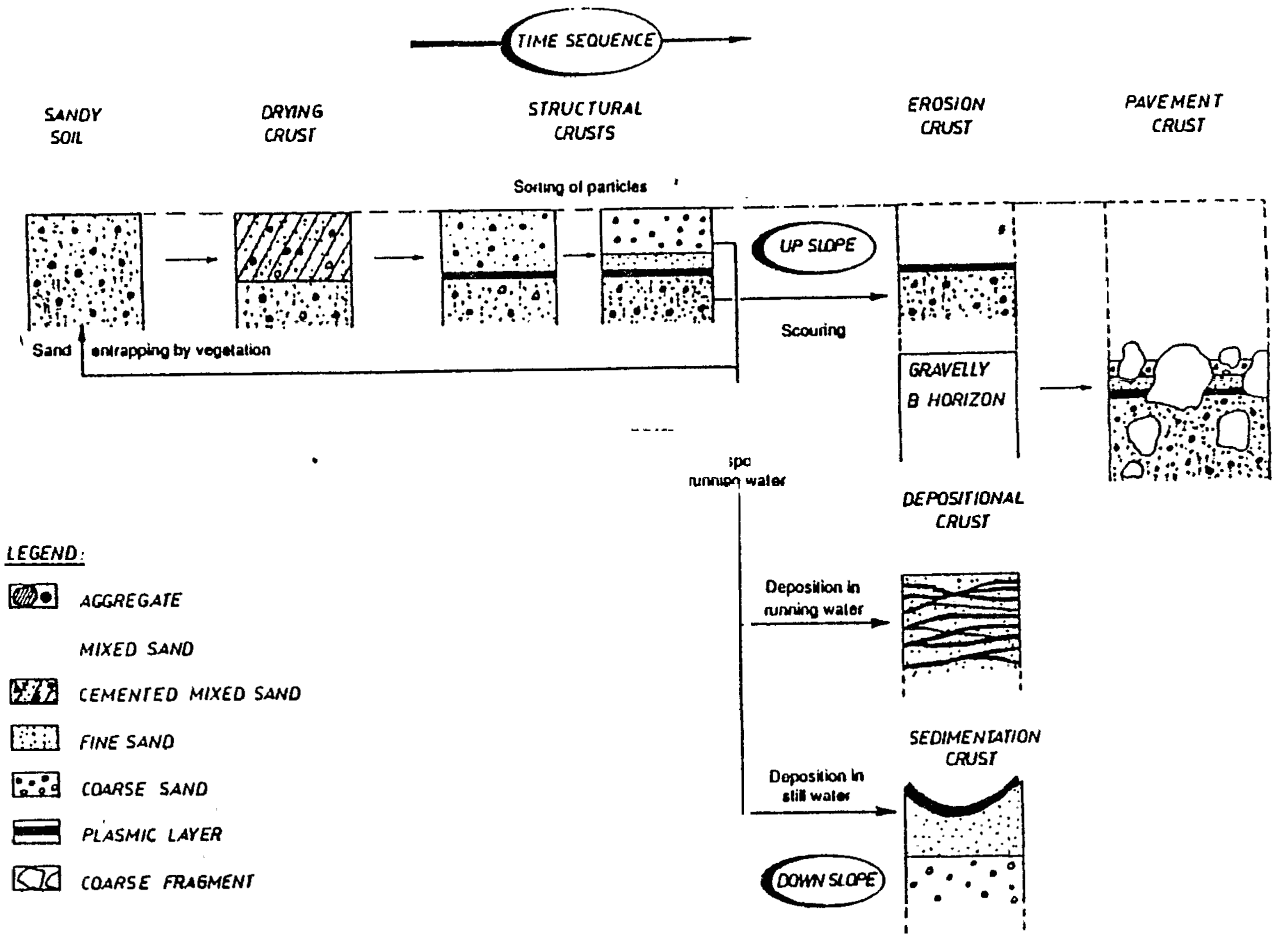


Figure 1. Diagram showing processes involved and sequence of formation of the various types of crusts (after Bresson and Valentin, 1990).

surface layer is tightly bound by a combination of bacterial slimes and prolific algal and fungal hyphae (Figure 2). Upon drying these crusts are torn and curl upwards. Their effect on water infiltration under wet conditions were not studied. Similar crusts were reported on by Hutson (1971), Dulieu et al. (1977), Valentin (1981) and van der Watt and Claassens (1990).

The above-mentioned crusts are the most common on both cultivated and natural soils. However, several other types have been recognized and described, for example,

(i) white saline crusts resulting from salt accumulation near the soil surface (e.g. Brabant and Gavaud, 1985);
(ii) black saline crusts due to an accumulation of sodium carbonate (Aubert, 1976); and
(iii) yellow saline crusts on very acid sulphate soils (Le Brusq et al., 1987) composed mainly of aluminium, iron and magnesium sulphates.

These crusts are found mostly on clayey, alluvial soils and are therefore rather similar to sedimentation crusts with polygonally shaped cracks. However, in the dry season these crusts can evolve into a loose, powdery layer, as observed in northern Senegal by Mougenot (1983). The superficial saline crusts usually have a granulometric composition comparable to the top layer of soil, but with a much higher electrical conductivity and salt content (Hanna and Stoops,

Table 1. Main features and properties of the different types of surface crust in the Sahelian zone (after Casenave and Valentin, 1989).

Type	Structure	Thickness (mm)	Strength	Porosity
Drying	massive single sandy microhorizon	5-10	very low	high
Structural 1	rough surface made of coalescing partially slaked aggregates	> 10	low	moderate
Structural 2	laminar, a sandy microlayer over thin seal of finer particles	1-3	moderate	moderate
Structural 3	laminar, coarse sandy layer at the top vesicular fine sandy layer, seal of finer particles at the bottom	1-3	moderate	low
Erosion	smooth surface made of a single seal of fine cemented particles	< 1	high	very low
Aeolian	laminar, interbedding of sandy microlayers	2-50	low	high
Runoff deposition	laminar, interbedding of sandy microlayers and seals of finer particles	2-50	moderate	low
Sedimentation	laminar, larger particles at the top, finer at the bottom	2-50	moderate	low
Gravel	laminar, similar to structural 3, including coarse fragments	2-30	high	very low

1976).

B. Mode of formation

Several processes may be involved in crust formation, occurring either simultaneously or in succession. Casenave and Valentin (1989) distinguished four main processes : wetting, raindrop impact, runoff and drying.

Wetting is important in loamy and clayey soils. When dry soil is rapidly wetted, air entrapment occurs and pressure differences disrupt soil aggregates. Swelling (depending on clay mineralogical composition), occurring concurrently, further aids the disruption process (Valentin, 1991). Oversaturation of the uppermost few millimeters of soil results in suspended, dispersed clay which fills the particle interstices, thus forming a structural type surface crust (Table 1) (Hanna and Stoops, 1976; Collinet, 1988a). Slaking of dry aggregates due to rapid wetting can occur independently of impact forces (Valentin and Ruiz-Figueroa, 1987; Valentin, 1991).

Raindrop impact is the main cause of crusting on sandy soils. Sandy aggregates are quite fragile and therefore readily break down under raindrop impact. Crater-like features develop at the surface, with coarser particles on top of finer ones. This sorting process, together with the accumulation of finer particles above the zone compacted by raindrops (Valentin, 1986a),

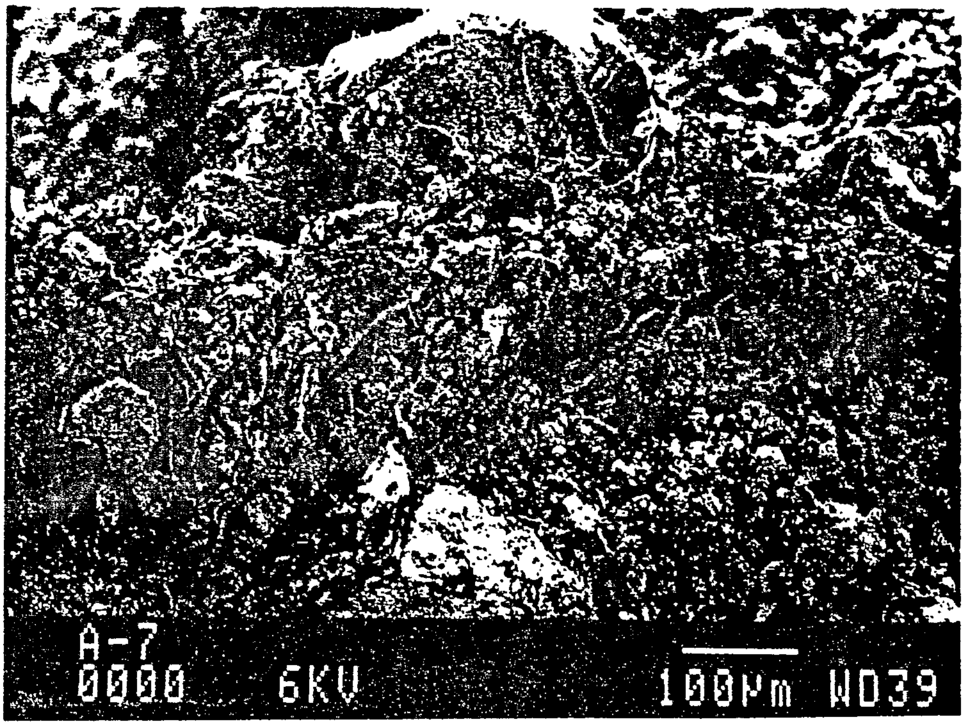


Figure 2. Surface crust stabilized by algal and fungal hyphae (after van der Watt and Claassens, 1990).

or above the zone of a compressed air layer (Collinet, 1988a; 1988b), are considered to be the most significant processes in the formation of Structural 1 and Structural 2 types of surface crusts (Table 1; Figure 1).

Runoff results in lateral movement of particles, combined with sorting. It favors the formation of a dense, laminated crust referred to as a "runoff depositional" crust (Table 1). When surface roughness decreases, runoff velocity (or wind velocity (Valentin, 1985)) increases. The one or two sandy microlayers of the Structural 2 or Structural 3 crust types are washed away, exposing the denser seal composed of fine particles, or the Structural 1 crust may be smoothed. If the process proceeds leaving coarser gravel behind, a gravel crust develops.

Drying increases the strength of a surface crust exponentially as a function of decreasing water content (Valentin, 1986b). Cracks and a curling up of platy structures can occur due to differences in shrinkage forces among the microlayers. This phenomenon is pronounced in the case of sedimentary crusts.

III. Methods Employed in the Study of Soil Crusts

A. Microscopy

1. Micromorphological studies

The microscopic study of thin sections provides a powerful method for examining soil surface crusts. It helps in characterizing the size and nature of the components and the arrangement and porosity of the microlayers forming the crusts.

Micromorphology was used to study surface crusts of saline soils in Egypt (Hanna and Stoops, 1976), on cropped soils in the Ivory Coast (Blic, 1979), in Burkina Faso (Kooistra and Siderius, 1986), in Mali (Dutartre, 1989) and in Nigeria (Kooistra et al., 1990). The types of crusts formed under furrow irrigation were studied in Egypt (Bishay and Stoops, 1975) and under sprinkler irrigation in the Ivory Coast (Valentin and Ruiz Figueroa, 1987). In several studies, it was attempted to relate infiltrability, measured under simulated rain, to the microfabric of the surface crusts (Valentin, 1981; Escadafal and Fedoroff, 1987; Valentin and Ruiz Figueroa, 1987). Furthermore, significant insight into soil crusting processes has been gained by field collection of time-sequence samples under natural or simulated rain. Thus several stages of crust formation could be identified and crust genesis reconstructed in both space and time (Bresson and Valentin, 1990; Valentin, 1991).

2. Electronmicroscopy

Scanning electron microscope (SEM) studies of both artifical and natural soil crusts have been conducted on a number of South African soils. Levy et al. (1988a) found that on a Plinthustalf containing 20% clay and 74% sand, the microstructure of crusts was influenced by both ESP and whether the sample was taken from local microplains or mounds. At low ESP and in the microplains area, a compacted surface layer with primary particles partly stripped of clay was visible. At high ESP this layer could not easily be identified due to dispersed clay particles, which appeared to be homogeneously distributed over a 1 mm thick layer, masking other particles. No signs of a "washed-in-zone" (McIntyre, 1958) could be detected. Samples from the micromounds, on the other hand, did not show a compacted layer and the soil surface structure appeared to be only mildly affected by raindrop impact.

van der Watt and Claassens (1990) used SEM in attempting to evaluate the effect of gypsum and organic mulch treatments on the microstructure of crusts. The stabilizing effect of gypsum on the microaggregates was clearly visible, as was its effect in maintaining a "rougher" surface in comparison to crusts from soil which had received no gypsum.

Problems encountered with SEM studies are (a) the qualitative nature of the observations and (b) the tremendous variability from point to point, making objective conclusions somewhat difficult. Back-scattered electron scanning imagery (BESI) of thin sections is more satisfactory, making clear delineation of the microlayers possible (Bresson and Valentin, 1990). A further advantage of this technique is that information on porosity is gained for a region just a few micrometers below the crust surface.

3. Image analysis

Image analysis is a useful tool to assess the distribution, size and shape of the pores in the microlayers within the crust (Kooistra et al., 1990). Valentin (1991), using image analysis, showed that the porosity at the surface of clod remnants was greater than that of the runoff crusts in lower areas.

B. Aggregate Stability

Valentin and Janeau (1989) in an attempt to predict crusting under simulated rain in the field, evaluated the applicability of various aggregate stability indices for 20 wet savannah soils from the Ivory Coast. They concluded that no single index can be used to predict surface crusting since the antecedent moisture content and the rainfall characteristics are determining factors in the processes involved. Thus care should be exercised in applying aggregation indices to crust formation.

C. Crust Strength Measurements

Measurements of crust strength were made by Hutson and Sumner (1970) and Hutson (1971) in order to obtain a quantitative measure which could be related to soil properties and plant response. Crust strength was measured using the modulus of rupture technique (Richards, 1953). It was found that the modulus of rupture is strongly dependent on the bulk density of the bricquettes, irrespective of the method used to increase bulk density. The bulk density was found to increase with increasing ESP, due to dispersion and a resultant close packing of particles. Thus it is important to realize that apart from the shattering effect of raindrops which promote crust formation, crusting is further encouraged by particle reorientation resulting from chemical dispersion effects due particularly to the ESP. In this investigation it was also found that there is a threshold ESP value for a particular soil below which the modulus of rupture is constant. This implies that in practice, if the ESP is maintained at any value less than the threshold value, crust formation due to dispersion will not easily occur.

Ruiz Figueroa (1983) simulated seedling emergence through a crust using a laboratory penetrometer which recorded the energy required to force a probe upwards through a soil sample. The probe was connected to a beam balance which was gradually loaded with water on the side opposite to the probe. It was shown that surface strength increases exponentially with a decrease in water content of the crust.

In northern Niger, Valentin (1986b) employed a Proctor needle (circular flat probe) to measure the force required to penetrate crusts. Results showed that on tilled sandy soils, crust strength measured in this way increased mainly with increasing cumulative kinetic energy of antecedent rain, whereas clayey crusts tended to harden more during drying. This finding agreed with results for millet seedling emergence in southern Niger (Valentin, 1981). In the latter study it was found that seedling emergence of millet was 40% on a plot that had received preponding rain with energy 40 J M^{-2}, whereas it was only 20% when the rain energy was 81 J m^{-2}.

D. Infiltration Rate Measurements

1. Laboratory studies

The development of laboratory-type rain simulators, such as that of Morin et al. (1967), to a large degree gave impetus to more detailed studies of crust formation and the factors controlling it. Levy (1988) and Smith (1990) used infiltration rate measurements, under simulated rain conditions, to examine the influence of factors such as clay mineralogy, exchangeable cation composition, cultivation and some of the soil forming factors on soil crusting. These results will be discussed later. Levy et al. (1988a) used a micropermeameter (9 mm inner diameter) to differentiate between the hydraulic conductivities of surface features of artificially formed crusts.

Rose (1960) used a dropper-type rain simulator to study the detachability of soils from Uganda, Kenya and Tanzania. Rainfall rates could be varied by altering the number of droppers and by changing the head of water above the droppers. Elwell and Makwanya (1980) developed a rainfall simulator in Zimbabwe which could be used for both laboratory and field studies. This simulator was capable of reproducing the drop-size distributions and kinetic energy of a high intensity storm; energy levels could be varied by adjusting the duration of the applied storm.

2. Field studies

A large number of different types of rain simulators have been used to study infiltration rates in the field. In most cases, the primary objectives were to study soil loss by water erosion and to quantify the parameters in the universal soil loss equation (USLE). In South Africa, much work of this nature has been done by particularly the Division of Agricultural Engineering using a rotating boom simulator developed by Swanson (1965) (e.g. Mallett et al., 1981; Crosby et al., 1983, McPhee et al., 1983; McPhee et al., 1983; Lang and Mallett, 1984; McPhee and Smithen, 1984). ORSTOM researchers also used a boom-type rain simulator to study infiltration and soil loss in the Ivory Coast, Burkina Faso and Niger (Lafforgue and Naah, 1976; Collinet and Valentin, 1984; Collinet, 1988a).

Data obtained by rainfall simulator trials have provided a valuable first approximation of essential data required especially in respect of soil erodibility and the efficacy of soil conservation practices. In most cases crusting *per se* was not studied, and the relationship between the crusting properties of soils and runoff and erosion are not precisely known. It was, however, repeatedly shown that protection of the soil surface either by growing vegetation or surface applied mulches reduced runoff dramatically. By inference, soil crusting caused by raindrop impact is reduced under these conditions.

Very useful oscillating nozzle, sprinkling type rain simulators for field use were independently developed by Asseline and Valentin (1978) and van der Watt and Claassens (1990). The equipment is easily portable and rainfall intensity is variable from 30 to 140 mm h^{-1}. It is also possible to vary drop size and drop velocities by using different nozzles and water pressures (van der Watt and Claassens, 1990).

The double-ring infiltrometer has been used in some studies pertaining to soil crusting (Wilkinson and Aina, 1976), but is not very satisfactory and has been criticized by several authors (Lafforgue and Naah, 1976; Valentin, 1981; Poss and Valentin, 1983; Valentin, 1988) since it yields infiltration rate values quite different from those recorded under natural or simulated rain.

IV. Factors Affecting Crust Formation

Some soils are undoubtedly more prone to crusting than others. The permanence of a crust formed under conditions of water application also varies greatly - e.g. self-mulching clay soils have a discontinuous crust, but when wet and other conditions favoring crusting prevail, a very dense crust with low hydraulic conductivity may form. Various attempts have been made to identify the soil factors favoring crust formation. Inconsistencies are frequently found when some demonstrated relationship is extrapolated, as are pointed out later.

A soil's susceptibility to crusting is not considered in the taxonomic classification of soils, although an important soil in South Africa, the Arcadia form (a Vertisol), is differentiated into series on the basis of its surface crusting properties. Generally, a wide range of soils exhibit the same crusting phenomena and type of crust. Therefore crusting and its consequences very frequently extend across soil classification boundaries, especially in the arid zones (Casenave and Valentin, 1989). In the more humid savannah zones, a better relationship between soil type and crusting tendency has been observed. For example, in well-drained red ferrallitic soils occurring on the upper part of hillslopes in the Ivory Coast, surface crusting occurs less than at lower elevations where yellow, massive, ferruginous-like soils predominate (Poss and Valentin, 1983; Planchon et al., 1987).

The factors involved in soil crusting may be grouped into two classes : those intrinsic to the soil and those due to external influences.

A. Intrinsic Soil Properties

1. Soil texture

Soil particle size distribution, particularly clay and gravel/cobble contents and relative proportions of the various soil separates, affect soil crusting. High clay contents generally favor aggregation and reduce the rate of crust formation, although clay mineralogy and exchangeable cation composition will modify this generalization. Medium-textured soils (< 20% clay) are usually very susceptible to crusting. It is probable that in extremely sandy soils the amount of clay, once dispersed, is not sufficient to clog the conducting pores at the soil surface.

Several studies have shown that the texture most prone to crusting consists of approximately 90% sand and 10% silt or clay. This was demonstrated in the laboratory by Poesen (1986) in a comparison of the sealing intensity of 8 binary mixtures, and in the field in

Table 2. Particle size analysis of sandy soils reported to be very prone to crusting (adapted from Poesen, 1988).

Soil location	Texture			Source
	Clay	Silt	Sand	
		%		
Adiopodoumé (Ivory Coast)	11.4	5.0	83.6	Lafforgue & Naah (1976)
Niono (Mali)	5.0	15.0	80.0	Hoogmoed (1986)
Sadore (Niger)	3.0	5.0	92.0	Hoogmoed (1986)
Agadez (Niger)	5.0	6.2	89.8	Valentin (1986a)
Owerri (Nigeria)	6.0	10.0	84.0	Boers et al. (1988)

West Africa by several authors (Table 2).

Surface gravel and cobbles may either increase or decrease soil crusting. In the arid zone of west Africa, soils containing coarse fragments are usually severely crusted (Casenave and Valentin, 1989). Conversely, in wet savannah and in the rainforest zone, gravel originating from disintegrated ironpans usually remains free on an uncrusted topsoil (Collinet and Valentin, 1979a; Collinet, 1988a; 1988b; Casta et al., 1989). In other studies, coarse fragments protected the smaller surface aggregates from raindrop impact - in the same way as a mulch - thus

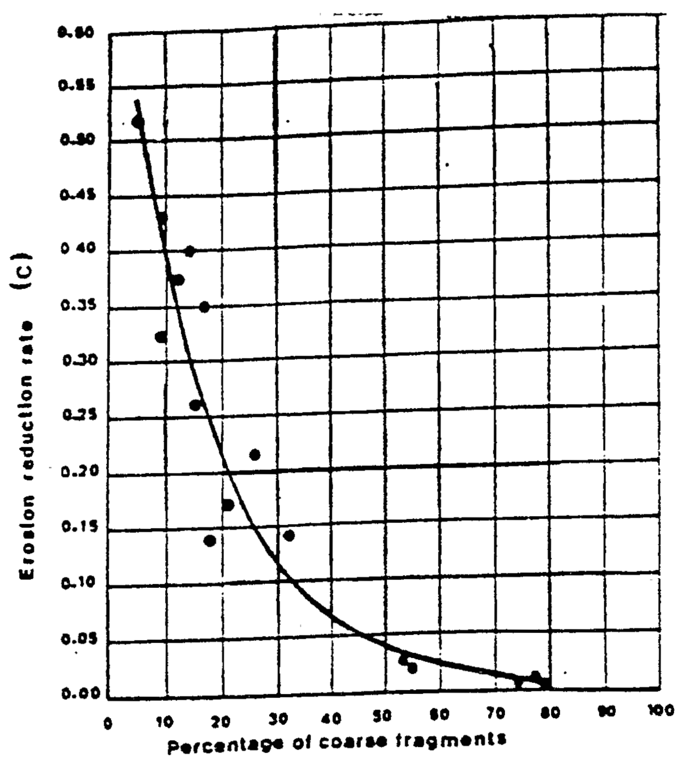


Figure 3. The influence of coarse surface fragments on the reduction of soil erosion (from Collinet and Valentin, 1984).

increasing infiltration and reducing erosion (Collinet and Valentin, 1984) (Figure 3).

2. Clay mineralogy

In Europe and the USA, most studies on soil crusting were conducted on soils containing predominantly micaceous clays and/or smectites. Levy and van der Watt (1988) studied the effects of clay mineralogy and ESP using four South African soils, and compared their results with those for four comparable soils from Israel. Some of their results are shown in Table 3.

Table 3. The clay mineralogy, exchangeable sodium percentage (ESP) and final infiltration rate (FIR) for the SA soils studied and for four Israeli soils

Soil	Country[a]	Dominant clay[b] minerals	ESP	C.E.C.[c]	Clay content	FIR
				cmol(C^+)/kg	%	mm h^{-1}
Hutton(Z)	SA	K(4),Is[d](2),St(1)	2.4	72.8	7.0	22.8
Typic Rhodoxeralf	IL	St,K	2.2	65.4	7.8	4.4
Avalon	SA	K(4),1(2),St(2)	2.7	40.5	20.0	5.5
Typic Rhodoxeralf	IL	St,K	2.2	59.3	19.2	2.0
Hutton(H)	SA	K(5),I(1)	2.9	9.5	29.6	6.5
Typic Rhodoxeralf	IL	St,K	2.5	76.0	32.0	3.2
Swartland	SA	I(4)Is[e](3)	2.1	43.6	14.9	4.2
Typic Rhodoxeralf	IL	St,K	2.5	81.7	15.9	2.6

[a]Country of origin of the soil: SA = South Africa, IL = Israel
[b]I = Illite, Is = Interstratified material, K = Kaolinite, St = Smectite, (1) = very weak, (5) = very strong.
[c]C.E.C. = Cation exchange capacity of the clay fraction of the soils.
[d]Is = material containing 1:1 clay components.
[e]Is = material containing swelling components.

The measure of crusting employed in this study was the final infiltration rate (FIR) calculated from Morin and Benyamini's (1977) non-linear regression equation describing the curve relating infiltration rate (I_t) to elapsed time (t):

$$I_t = FIR + (I_t - FIR)\, e^{-Ypt}$$

in which I_i = initial infiltration rate, Y = a curve-fitting parameter related to the stability of the soil aggregates and p = rain intensity. For any clay content, the FIR values for the South African (SA) soils were always higher than those for the Israeli soils. The kaolinitic soils from SA maintained FIR values in the range 5-23 mm h^{-1}, which were in good agreement with the results of Miller (1987), who studied infiltration and soil loss on three kaolinitic soils in the U.S. It was concluded that if the dominant clay mineral of the clay fraction is kaolinite, crusting should be less serious, although the presence of even small amounts of smectite and/or micaceous minerals could drastically increase the soil's crusting tendency. Furthermore, the presence of free iron in soils from the humid to subhumid tropics would also have a stabilizing effect. In West Africa, Collinet (1988b) also concluded that the more stable soils contained mainly kaolinite while soils containing smectite and illite were most prone to crusting.

Smith (1990), in his study of the relationship between soil crusting and degree of weathering of red soils in South Africa, found that the more highly weathered soils, in which there were lesser amounts of 2:1 clay minerals, were more resistant to crust formation (Table

Table 4. Calculated cumulative infiltration (CI) after 100 mm of rain and measured final infiltration rates (FIR).

Parent material	Degree of weathering	CI (mm)	FIR (mm h^{-1})
Basic rocks	Low	34.59	8.49
	Medium	43.45	9.11
	High	66.95	18.60
Acidic rocks	Low	24.32	6.76
	Medium	31.95	9.00
	High	42.85	10.94

4).

3. Carbon content

It is well-known that organic matter is one of the most important aggregate stabilizing agents in soil. The very high organic matter decomposition rates in the warmer climates, of course, make it difficult to maintain high carbon levels in cultivated soils. Furthermore, one must be aware that organic carbon content and aggregate stability are subject to seasonal variation (Quantin and Combeau, 1962; van der Watt, 1987).

The effects of organic carbon on aggregate stability and resistance to surface crusting, have been studied on various soil types in the Central African Republic (Quantin et al., 1962), Senegal (Charreau and Nicou, 1971), Nigeria (De Vleeschauwer et al., 1978) and the Ivory Coast (Valentin and Janeau, 1989). The positive effect of organic matter on structural stability is more pronounced on sandy than on the more finer textured soils. If the ratio R = organic matter (%)/(silt + clay)(%) is considered, then four classes of soil with regard to crusting hazard were distinguished in 195 soil samples collected in Burkina Faso, Cameroon, Mali, Senegal, Tchad and Togo (Pieri, 1989). Crusting hazard is greatest when R <5% and least when R >9%. The threshold between low and high crusting susceptibility occurred when R = 7%.

In southern Africa, Elwell (1986) showed that on a fersiallitic clay soil in Zimbabwe, the mean weight diameter (MWD) of water-stable aggregates was highly significant in explaining variations in both soil loss and runoff. Organic carbon percentage in the soil very clearly determined the MWD of water-stable aggregates. The MWD increased from about 0.3 mm at 1.1% organic carbon to 3 mm when the organic carbon increased to about 2.4%.

When soils are cleared and cropped, susceptibility to crusting is increased and this can be related to the organic carbon content. The aggregate stability of two loamy sands from Ife, Nigeria, as measured by the wet sieving technique, ranged from one-fifth to one-third those of soils under secondary (15 to 25 years old) bush fallow and which contained about four times more organic matter than the cultivated soils (Aina, 1979). The recovery, under bush fallow, of soils previously cultivated requires a considerable time, at least ten years according to Valentin and Janeau (1989).

In South Africa, Smith (1990) studied the effects of cultivation and, by implication, of organic carbon on the crusting of a number of red soils. The final infiltration rates (FIR) as determined with a laboratory type rain simulator are given in Table 5 for the various soils studied. The data show that cultivation has an important adverse effect on FIR only under conditions of low weathering status (more arid conditions). Apparently, the stabilizing effect of sesquioxides and the already high organic carbon levels in soils from higher rainfall areas are responsible for the stability of these soils even when cultivated.

Table 5. Effect of cultivation on FIR of red soils derived from basic and acidic parent materials and developed under varying weathering intensities

Soils	Final infiltration rate (FIR) ($mm\ h^{-1}$)	
	Uncultivated soils	Cultivated soils
From basic parent material		
Weathering degree: low	14	6
medium	12	5
high	29	28
From acidic parent material		
Weathering degree: low	11	6
medium	11	11
high	11	11

4. Sesquioxide content

The stabilising effect of Fe and Al hydrous oxides and oxides are commonly regarded as an important factor in aggregate formation. Farres (1987) tested the aggregate stability of 20 soils from Mozambique and found that higher amounts of iron were associated with greater soil stability to the effects of raindrop impact. Obi et al. (1989) found that the percentages of water-stable aggregates (wet-sieving technique) of five sandy soils in southeastern Nigeria were high (70-92%), despite the relatively low organic matter contents (1.0-1.8%). These authors suggested that sesquioxides may play a key role in the stabilisation of these soils.

The positive effect of a high Fe_2O_3 + Al_2O_3 content on maintaining a good infiltration rate under simulated rain was shown by Smith (1990). With increasing degree of weathering (as described by climatic factors), the silica:sesquioxide ratio increased and resistance to crusting decreased (Figure 4).

5. Exchangeable cations

It is well known that a high percentage of exchangeable sodium (high ESP) and in some cases of exchangeable Mg, favors clay dispersion (van der Merwe and Burger, 1969; Kijne and Bishay, 1974). This in turn would increase soil crusting. In this regard the critical ESP (or

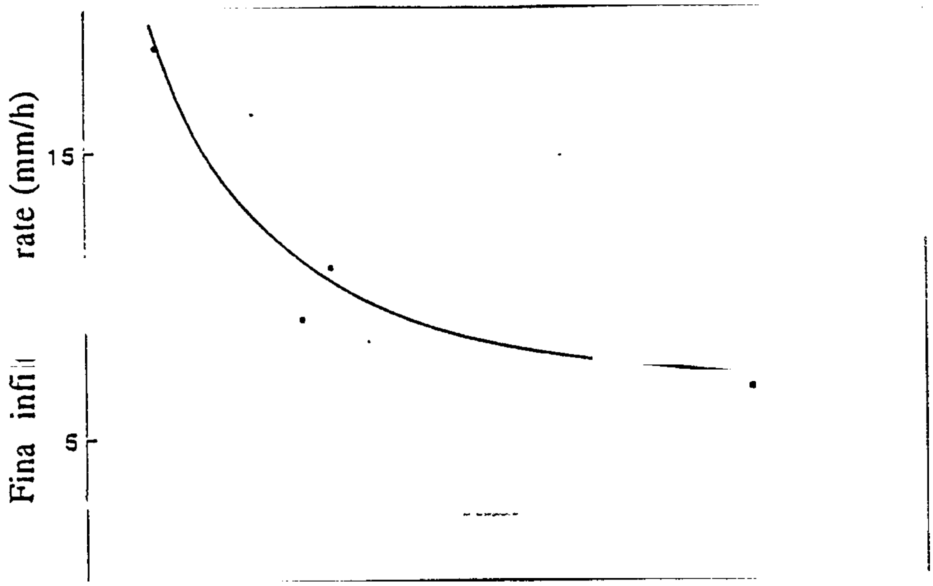


Figure 4. Relationship between final infiltration rate and silica:sesquioxide rate (after Smith, 1990).

critical EMgP), that is, the ESP below which crusting is not affected by ESP, is of the utmost importance, particularly in the case of irrigated soils. Many studies have been conducted in this regard, and it has emerged that the critical ESP differs greatly between soils and is moreover affected by other chemical factors, for example, electrolyte concentration of the irrigation water and clay mineralogy.

Levy and van der Watt (1988) studied the effects of clay mineralogy and soil sodicity on crusting of four South African soils. The effect of ESP on crusting differed widely : some soils

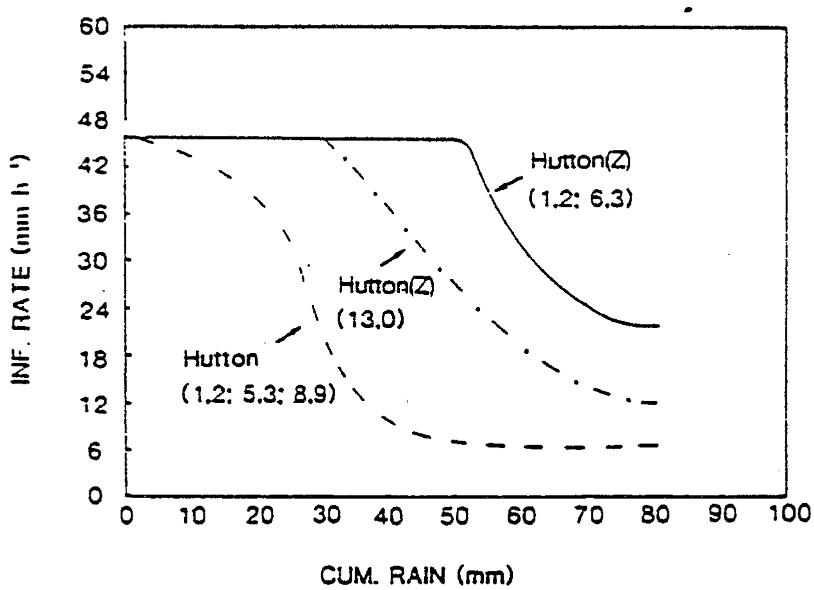


Figure 5. The effect of soil ESP on the infiltration rate of two stable kaolinitic soils (compare Table 6) (after Levey, 1988).

Table 6. Effect of ESP on final infiltration rate (FIR) and cumulative infiltration (CIF) (after 100 mm rain) of four South African soils.

Soil	Clay (%)	Dominant clay minerals [b]	ESP	FIR (SNK)[a] (mm hr^{-1})	CIF (SNK) (mm)
Hutton (Z)	7.0	K(4)[c],IS[d](2),ST(1)	1.0	21.3 a	85.2 a
(Rhodic Paleustalf)			6.3	21.9 a	85.9 a
			13.0	11.0 b	63.4 b
Avalon	20.0	K(4),I(2),ST(2)	< 1.0	12.9 a	43.1 a
(Plinthustalf)			4.8	4.1 b	22.5 b
			9.7	2.7 c	21.5 b
Hutton	29.6	K(5), I(1)	1.2	6.7 a	38.6 a
(Oxic Paleustalf)			5.3	6.3 a	40.4 a
			8.9	5.4 a	38.7 a
Swartland	14.9	I(4), Is[e](3)	1.1	8.4 a	28.1 a
(Haplargid)			4.3	5.2 b	21.7 b
			11.3	2.5 c	14.1 c

[a]SNK = Student -Newman-Keuls test. Figures followed by the same letter within a column for each soil do not differ significantly at the 5% level.
[b]K = kaolinitic; Is = interstratified material; St = smectite; I = Illite; IS[d] = material containing 1:1 clay components; IS[e] = material containing swelling components.
[c]Figures in brackets indicate peak intensities on a scale of 1-5.

were hardly affected, others affected at high ESP only and others were affected at all ESP levels (Table 6). In all cases, a crust did form on the soil surface; the ease and rate of crust formation are apparent from the infiltration rate versus cumulative infiltration curves (Figure 5).

The Hutton soil, with ≈ 30% kaolinitic clay (mainly), is not significantly affected by ESP in the range 1.2 to 8.9%. The Swartland soil, containing less clay and with mainly illite and interstratified minerals in the clay fraction, is already significantly effected at ESP 4.3 with a further reduction in FIR at ESP 11.3. The Avalon soil, although kaolinitic, contained some illite and smectite and behaves like the Swartland soil. The Hutton (Z) soil is affected only at high ESP. Smith (1990), using a group of red soils, found that ESP did influence the FIR, but did not decrease it to very low levels. These soils, pretreated with water of SAR 10, had FIR's not lower than 7-8 mm h^{-1} and as high as 12.5 mm h^{-1}.

Exchangeable potassium was also found to have an influence on crusting. Using three of the same soils referred to in Table 6, Levy and van der Watt (1990) found that by increasing the amount of exchangeable K, a decrease of both the hydraulic conductivity and FIR resulted.

It was found that relative to Ca and Na, exchangeable K had an intermediate effect. For example, on the Swartland (Haplargid) soil an ESP of 11.3 resulted in a FIR of 2.5 mm h^{-1}, whereas an EPP of 15.5 resulted in a FIR of 6.7 mm h^{-1}.

Magnesium is sometimes regarded as a dispersive cation, particularly with regard to its effect on hydraulic conductivity (van der Merwe and Burger, 1969). Levy et al. (1988b) showed that the effect of magnesium differs for HC and FIR measurements. HC measurements are more sensitive to dispersion than FIR, and Mg influenced the former but not the latter. For example, for the Swartland soil referred to above, at an ESP of 1.0, a Na-Ca saturated clay had a FIR of 8.2 mm h^{-1} whereas the Na-Mg saturated soil had a FIR of 7.4 mm/h (did not differ significantly from the 8.2 mm h^{-1}). Collinet (1988a), on the other hand, found that West African soils are more prone to crusting when Mg/CEC is greater than 50%.

6. Soil water content

Aggregates "explode" more easily when they are initially dry and then wetted suddenly. Therefore slaking and dispersion occur more rapidly when rain falls on a dry soil, compared to a soil already wet (Valentin, 1981; Fapohunda, 1986; Valentin, 1986b; Collinet, 1988a).

7. Hydrophoby

A number of authors observed that the stability of surface crusts are enhanced by certain algae and/or fungi (Hutson, 1971; Dulieu et al., 1977; Valentin, 1981; van der Watt et al., 1990). Organic components are thought to be responsible for the phenomenon of hydrophoby observed in certain crusted sandy soils. The physical binding effect of hyphae are, however, more important for water infiltration than hydrophoby. It was observed that hydrophoby *per se* often disappears following a few millimeters or less of rain (Rietveld, 1978).

8. Topography and microtopography

A number of authors (Hudson, 1957; Roose, 1977; Stern, 1991) observed that runoff increases with increasing slope gradient up to a certain point, then levels off and even decreases on steeper slopes. Crusting processes, especially those related to kinetic energy of rain, are most pronounced on very low gradients. On steeper slopes, runoff and surface layer removal can be sufficient to remove the crust as it forms, thus preventing the sharp decrease in infiltration rate usually observed.

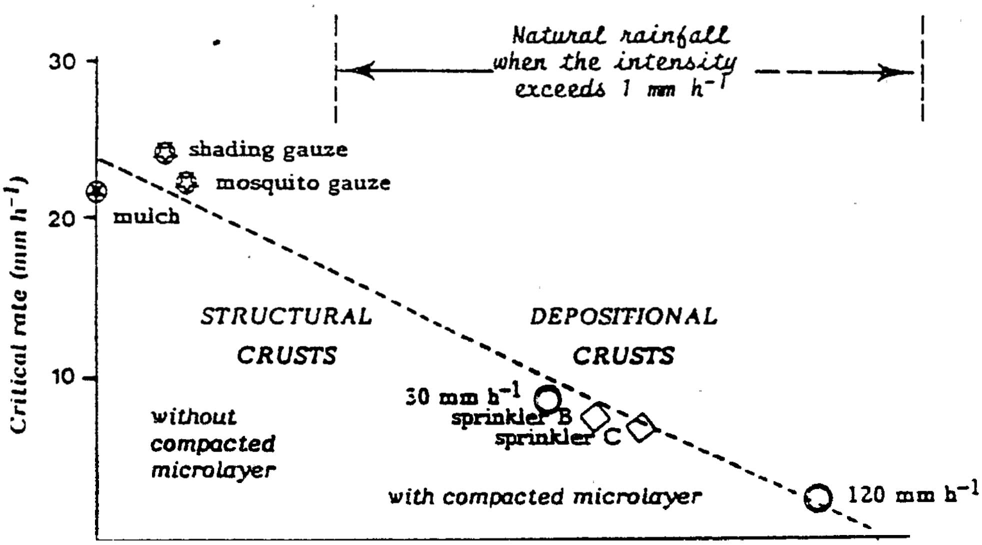
Microtopography and surface roughness affect crust formation and runoff in that the depth of water films at the soil surface, microslopes and water flow velocity are all influenced on a meso-scale. The result is that a number of crust types and the severity of crusting varies from the depressions to the tops of "mounds" (Collinet, 1988a; Levy et al., 1988a; Pleuvret, 1988; Casenave and Valentin, 1989). Thus runoff depositional or sedimentary crusts develop in the depressions whereas structural and erosional crusts are located on the more elevated zones.

B. External Factors

1. Kinetic energy of rain

Since the energy with which a falling waterdrop strikes the soil surface is clearly related to its shattering effect on the aggregates, measurement or calculation of the kinetic energy of waterdrops striking the soil surface is very relevant. Both drop size (mass) and impact velocity determine kinetic energy, and the latter depends on the former. The drop size distribution of a rainstorm or simulated rain therefore is of paramount importance. For natural rain the distribution varies both regionally and seasonally (Casenave and Valentin, 1989). Limited available data suggest that raindrops are larger under continental conditions, for example, in northern Nigeria (Kowal and Kassam, 1976) and in Zimbabwe (Hudson, 1973) than in climates subjected to oceanic influence (Casenave and Valentin, 1989).

In the case of rain simulators, drop size distribution should approach that of natural rain, for the same intensities. This is almost achieved with the oscillating nozzle type simulator developed by Asseline and Valentin, (1978). At low intensities the nozzle is oscillated at a larger angle, so that only finer drops fall within the experimental plot. Conversely, at high intensities the whole range of drops, including the largest, are sprayed over the experimental plot. Valentin (1979) furthermore used a simple method to determine the impact velocity of the drops. A physical relationship was used to derive impact velocity and maximum velocity in air. Initial velocity was determined by pointing the nozzle horizontally and measuring the distances to which the drops were projected. Using a similar rain simulator, van der Watt and Claassens (1990) estimated the kinetic energy of simulated rain with a median drop diameter of 4.5 mm



at 66.1 J mm^{-1} m^{-2}, which is considerably higher than the 18.1 J mm^{-1} m^{-2} calculated for the much-used rain simulator described by Morin et al. (1967) (according to Levy, 1988). Valentin and Ruiz Figueroa (1987), using rains with different kinetic energies and various types of soil cover (sugarcane residue mulch, shading gauze and mosquito gauze) showed that, for a sandy loam soil in the Ivory Coast, soil crusting was directly related to rain kinetic energy (Figure 6). Seasonal rainfall energy in Zimbabwe ranged from 9080 to 20560 J m^{-2}, and was found to be closely related to erosional soil loss (Elwell, 1978).

Hudson (1973) clearly demonstrated the effect of rain kinetic energy on erosion by placing mosquito gauze over experimental plots. The kinetic energy of the rain before runoff occurs is of greatest importance for crusting, since once the surface is covered by a water film the effect of raindrop impact is reduced (Valentin, 1986b; Collinet, 1988a). Hudson (1957; 1963; 1965) studied the drop-size distribution and energy of rainstorms in Zimbabwe in some detail, and perfected the flour-pellet method for the determination of drop sizes.

2. Irrigation

The composition of irrigation water, particularly in respect of its sodicity and electrolyte concentration, determines the ease of chemical dispersion of the soil aggregates. These effects were studied, among others, by Levy (1988) and Smith (1990) using a number of soils from South Africa. Some of their results have already been referred to. It should be noted that clay mineralogical composition is an important consideration when evaluating these effects (Levy and van der Watt, 1988). Even water with a low sodium and carbonate content, such as the water from the river Niger near Niamey can induce surface degradation (Valet, 1990). Considering three methods of irrigation water application in Nigeria, Fapohunda (1986) found that wetting of soil by flooding is more destructive than by furrow or trickle irrigation. On the other hand, Bishay and Stoops (1975) in Egypt and Valet (1990) observed thick crusts formed by furrow irrigation.

3. Wind action

Wind acts as an agent of erosion. Particles are sorted, transported and deposited by wind. The weakest microlayers of surface crusts, that is, the sandy microlayers of structural type 1 and 2 crusts, are removed by wind and the surface seal exposed, forming an erosion crust (Figure 1). When wind-blow sand is entrapped by surrounding vegetation, it usually forms a drying crust which can evolve into structural type 2 or 3 crusts. On dunes, almost devoid of fine particles, the deposited sand may form a laminated crust referred to as an aeolian crust (Casenave and Valentin, 1989). In the Sahelian zone, wind plays an important role in creating surface heterogeneity. Barren spots covered with an erosion crust is usually surrounded by sandy aeolian micromounds covered by grass vegetation (Aubert and Maignien, 1948; Valentin, 1985).

4. Human and animal influences

Termites may either create or destroy surface crusts. Foraging termites like *Trinervitermes* harvest grass vegetation near their nests, leaving the soil bare and severely crusted (Janeau and Valentin, 1987). Fungus growing termites such as *Cubitermes* are thought not to have much impact on crusting. Other species such as *Macrotermes* may cause crusting due to erosion of their cathedral-shaped nests, but they also build tunnels at the soil surface as protection against light, thereby perforating the surface and reducing crusting.

Earthworms of course promote the formation of soil aggregates. In the wet savannah zone, Lavelle (1983) showed that earthworms ingest 700 m^3 soil ha^{-1} $year^{-1}$ and their casts amount to 30-40 m^3 ha^{-1} $year^{-1}$. Blanchard et al. (1991) found that the strong aggregation produced by *Millsonia anomala* directly depended on earthworm biomass. Furthermore, earthworm casts are resistant to slaking. Earthworms also perforate already-formed surface crusts, thus enhancing infiltration (Casenave and Valentin, 1989).

Cattle have an ambivalent effect on soil crusting. They reduce vegetative cover and trample the soil, which promotes crusting especially on loamy and clayey soils. Overgrazed areas may thus evolve into severely crusted areas (Leprun, 1978; Casenave and Valentin, 1989). On the other hand, trampling may reduce surface crusting on sandy soils, and the droppings enhance surface structure.

Humans may influence soil crusting both directly and indirectly through agricultural practices and other land uses. Path formation and vehicle compaction (Garland, 1983), tillage (Wilkinson and Aina, 1976), levelling processes (Gaheen, 1987) and cropping sequences (Charreau and Tourte, 1967; Omar, 1983) have all been shown to affect crust formation to some degree.

Table 7. Final (one hour) infiltration rates (FIR) of plots at beginning and end of a growing season (van der Watt and Claassens, 1990).

Treatment		FIR at planting	FIR at harvest
Gypsum	Mulch		
($t\ ha^{-1}\ crop^{-1}$)		($mm\ h^{-1}$)	
0	0	22.2	10.1
0	4	27.8	24.2
0	8	33.0	23.6
2	0	27.2	22.1
2	4	48.0	33.2
2	8	46.3	40.4
5	0	40.8	30.0
5	4	62.9	33.2
5	8	64.1	53.5

5. Soil cover

The shattering effect of raindrops is obviously diminished by various types of soil cover, in particular vegetative cover and mulches. van der Watt and Claassens (1990) described work in which the effects of both surface-applied phosphogypsum and mulches, each at three application levels, on infiltration rate were studied. Some of their results are shown in Table 7. It is noteworthy that the "FIR" (one-hour "final" infiltration rate) at the end of the growing season is doubled by application of 4 t ha^{-1} mulch, in the absence of gypsum. When gypsum is added, the FIR is increased even further.

Maximum efficiency is obtained with a surface mulch, since in the case of tall vegetation, drops form anew, in which case they may be larger than the original raindrops and if falling from a sufficient height, may reach their terminal velocity. Collinet and Valentin (1979b) showed that the kinetic energy of rain at the soil surface under a tree can be similar to that of free falling rain.

V. Consequences of Soil Crusting

B. Physical Consequences

1. Infiltration and runoff

In areas where biomass production is limited by soil water availability, the efficiency of rainfall and of water applied by overhead irrigation systems are adversely affected by soil surface crusting. Many studies have been aimed at a direct evaluation of infiltration as influenced by the crusting phenomenon (Wilkinson and Aina, 1976; Collinet and Valentin, 1979a; Imeson, 1983; Chevallier and Valentin, 1984; Hoogmoed and Stroosnijder, 1984; Albergel, 1987; Albergel and Valentin, 1988; Collinet, 1988b; Levy 1988; Casenave et al., 1989; Valentin and Casenave, 1990; Valentin et al., 1990; van der Watt and Classens, 1990; Smith, 1990; and many others), while others (most) are concerned with soil loss and erosion which indirectly relate to surface crusting. Runoff and erosion studies have been conducted on both field-plot and catchment scales. A comprehensive bibliography (more than 500 references) of southern African work in this regard has been compiled by Weaver (1989). The properties of surface crusts have been used by Valentin (1986c) and Albergel (1987) to predict water flow from small Sahelian watersheds. In this approach the typology of surface crusts (Table 1) was incorporated in a classification of unit surfaces including relief, vegetative cover and faunal activity. This classification (Casenave and Valentin, 1989) is linked to the key hydrological factors of infiltration coefficients and rates for different soil water conditions, and was extended to watershed runoff prediction using a specific mapping method.

Lal (1990) discussed the severity of soil erosion in many parts of Africa and attributed it to high population density, soils that are highly prone to erosion due to intensive arable land use and harsh climates, uncontrolled grazing and excessive stocking rates. Surface crusting undoubtedly also plays an important role.

2. Surface spectral properties

The degradation of surface structure is reflected in the albedo, especially in the arid zones (Courel, 1983). In severely crusted soils of southern Tunisia, coarse elements were shown to reduce the general reflectance whereas the Munsell color of the surface was highly correlated with the reflectance in the three wavelengths corresponding to red, green and blue (Escadafal, 1989). The reflectance of saline crusts in southern Senegal was also studied (Mougenot and Zante, 1986). More recently, the spectral properties of the various types of crusts listed in Table 1 were assessed in Niger (Courault et al., 1991).

3. Water and wind erosion

Water erosion as related to the adverse effects of soil crusting on infiltration has been discussed somewhat in 1 above. However, some anomalies are encountered. For example surface crusts are very effective in protecting soil against accelerated erosion (Kowal, 1974; Roose, 1977; Valentin, 1981). Obviously, the relationship between runoff (water) and soil loss is complex and influenced by soil crusting also. Severely crusted surfaces can promote runoff and limit erosion upslope, but result in more severe erosion downslope (Planchon et al., 1987). Erosion can also be related to the time sequence of crust formation. Soil detachment can be very high during the formation of a structural crust (Valentin, 1981; Collinet, 1988a), but the sediments could initially not be exported due to surface roughness being maintained while runoff depositional crusts or sedimentary crusts develop *in situ*. Also, soil loss may be less from an erosion crust, but because of greater surface smoothness, sediments can be exported over greater distances.

B. Biological consequences

1. Seedling emergence

Hutson (1971) reported on experiments in which the effect of crust strength of a Hutton Shorrocks (Rhodic Paleustalf) soil on the emergence of wheat seedlings was studied. Emergence occurred only when the modulus of rupture was below 400 millibar. Not all crusts need seriously limit seedling emergence, as in the case of sandy crusts (drying, structural 1 and 2 types) and sedimentary crusts (often because of cracks).

2. Agricultural productivity

It is usually difficult to assess the contribution of a single soil physical factor to an increase or decrease in crop yields. Surface crusts may adversely affect seedling emergence and water storage in soil and thus influence plant density and crop yield. In the Central African Republic, Combeau et al. (1961) found a significant relationship between cotton yield and aggregate stability ($n = 42$, $r = 0.595$, $P < 0.001$). More recently, in Togo, the production of cotton could be related to the morphological types of surface crust, referred to in Table 1 and Figure 1 (Audebert and Blavet, 1991). On the other hand, van der Watt and Claassens (1991) could not detect any significant effect of soil crusting on the yield of a number of crops under sprinkler irrigation on the Makatini Flats (Natal).

3. Effect on vegetation

In the semi-arid zones of west Africa, a vegetation pattern known as "tiger bush" has been ascribed to the occurrence of surface crusting. It consists of alternate bands of bush and bare and crusted soils. Courault et al. (1990) described the bare zone, covered with gravel and erosion crust, as an impluvium or catchment for the thickets where sedimentary and drying crusts prevail, and where soil fauna are active. These authors suggest that the dynamics of the system is controlled by the interactions between surface crusting, vegetation and faunal activity.

Because of their effect on infiltration and hence soil water storage, surface crusts may result in the spreading of barren spots and sometimes the intrusion of foreign species into these areas. Albergel amd Valentin (1988) described a "sahelisation process" in the Sudanese zone, in which an erosion crust which develops at the soil surface results in the introduction of typically drought resistant species more common in the Sahel zone. In the wet savannah zone, Mitja (1990) found that on a mechanically cleared field, the recovery of fallow vegetation is hampered by the formation of surface crusts which favor infestation by *Imperata cylindrica.*

C. Beneficial Effects of Soil Crusting

In arid and semi-arid regions, surface crusting is not invariably detrimental to crop growth since in some areas overland flow can be managed more effectively for agricultural production. Reij et al. (1988) reviewed water harvesting techniques, mainly in Africa's drought-prone zones. Some of them are very old, such as the terraced wadi systems in southern Tunisia, called "jessour" and described by Bonvallot (1986). Water is collected from small channels across mountain slopes into earth dams which reduce the flow velocity, increase storage and permit the accumulation of sediments. Thus cereal and tree crops are possible in zones with as little as 100-200 mm annual rainfall. A similar system is found in Lybia (Bruins et al., 1986).

In a simpler technique, water is conveyed from surface-crusted micro-catchments to basins made from earth mounds a few tens of centimetres high and shaped into a V or half-circle. Such techniques are used in Niger, Burkina Faso, Cape Verde and Libia (Reij et al., 1988). In the Ader Doutchi (Niger) and Mossi Plateau (Burkina Faso) areas, farmers construct stone piles on the contour to reduce runoff velocity from crusted areas and enhance infiltration.

VI. Soil Management for the Prevention/Control of Crusting

Our knowledge concerning the factors involved in soil crusting provides the logical steps that need to be taken for its prevention. The only problem, especially in Africa, will be to economically justify the technology required. For example, van der Watt and Claassens (1991) did not find significant yield increases for a number of crops in a field trial in which crusting was controlled by the use of gypsum and/or mulches.

The various management options can be classified as those requiring either physical soil and water manipulation and those requiring soil chemical amelioration.

A. Physical Soil Management

1. Tillage practices

Many experiments have shown that conservation tillage practices such as minimum tillage, surface mulching, strip-cropping, contour ploughing etc. will reduce runoff and soil loss (Mallett et al, 1981; Smithen, 1983). For arable agricultural production, tillage is an essential input.

The most suitable tillage practice does not necessarily cost much more and may be the most cost-effective management practice.

Since it is well-known that smaller clods are the first to slake (Valentin, 1981; Valentin and Janeau, 1989), seed-bed preparation should provide for large clods as well as sufficient fine material for efficient seed germination. However, this technique is inadequate on severely crusting soils (Valentin and Ruiz Figueroa, 1987). Moreover, its effect may be very short-lived (Hoogmoed and Stroosnijder, 1984; Serpantié, 1990).

Tie-ridging is a tillage practice designed to entrap water and to prevent runoff. A sedimentation crust tends to form in the basins, thus decreasing infiltration rates in those areas (Stroosnijder and Hoogmoed, 1984; Hulugalle, 1990). Furthermore, tie-ridges may accumulate water to the point of collapse, resulting in more severe erosion than would otherwise have been the case (Collinet and Valentin, 1984).

2. Mulching

An obvious way to protect the soil surface is by mulching. However, in many cases, plant residues have an economic value, as animal fodder, and therefore the economic benefits will be questioned. Wherever feasible and where undesirable side-effects (plant diseases) are absent, some type of minimum tillage practice is best suited to combat crusting. In some climatic zones, such practices may increase soil organic carbon content, but, in most parts of Africa, organic matter decomposition rates are so high that an increase in soil organic carbon is difficult to achieve (Theron, 1965; van der Watt, 1987).

Numerous studies have elucidated the specific effects (beneficial or otherwise) of plant residue mulches on surface crusting. It has been shown that mulching results in a rapid regeneration of surface structure (Scholte, 1989), the prevention of surface crusting (Kooistra et al.,1990), and an increase in faunal activity and hence favorable effect on surface crusting. However, there are also no negative effects. Valentin and Ruiz Figueroa (1987) found surface crusts even under thick sugarcane mulch, while residue mulching combined with zero tillage resulted in an increase in nematodes and root diseases in pineapple plantations (Valentin and Roose, 1990).

3. Improving vegetative cover

Avoidance of bare soil surfaces will combat crusting. In animal husbandry, it is essential to maintain the environmentally dictated stocking rates. In many areas, a grass ley farming system, among others directed at improving soil aggregation, has been advocated (Theron and Haylett, 1953). Usually, the Gramineae improve soil aggregation more effectively than other species (Damour and Killian, 1967). In the Central African Republic, aggregate stability could be recovered to the same level as under natural savannah by using a ley of *Pennisetum purpureum* or *Panicum maximum* for four years. Conversely, no improvement was observed with *Stylosanthes gracilis* and *Pueraria javanica* even after six years (Morel and Quantin, 1964; 1972). On the other hand, as reviewed recently by Young (1989), several trees or shrubs are thought to improve soil surface structure, e.g. *Acacia albida* in the Sahel (Dancette and Poulain, 1969) and pigeon pea (*Cajanus cajan*) in the wet savannah zone (Hulugalle and Lal, 1986).

Harmse and Nel (1990) showed that crusted, bare patches in natural veld had a lower water content in the top 300 mm of soil in relation to uncrusted areas. The patches could be revegetated with the aid of phosphogypsum applied at levels of 4 to 6 t ha^{-1}.

In arid and semi-arid regions, the food requirements of livestock and the use of straw for roofing make the use of mulches impracticable. However, an interesting technique is used in some places to rehabilitate crusted areas. Holes with a diameter of 10-30 cm are dug to a depth of 5-15 cm at intervals of 50-100 cm. Some manure, grass and soil are mixed and placed in the holes, followed by the sowing of millet and sorghum (Roose and Piot, 1984; Serpantié and Valentin, 1985; Mietton, 1986; Reij et al., 1988). In another technique branches and grasses are strewn over a barren and crusted spot. Termites that perforate the crust are attracted and wind-blown sand is trapped; within a year the spot is partly reclaimed (Casenave and Valentin, 1989).

4. Irrigation management

The chemical composition of irrigation water and the kinetic energy of water applied by overhead irrigation are the most important factors to consider in the case of irrigated soils. Where crusting occurs, precious water may be lost through runoff. If runoff water accumulates in local depressions, salt-affected spots may develop. The management practices required should take account of the sodicity of the water; where necessary, gypsum or phosphogypsum should be used. On soils highly susceptible to crusting, irrigation systems delivering high kinetic energy drops should be avoided. In the case of overhead irrigation, Valentin and Ruiz Figueroa (1987) insisted that the appropriate sprinkler systems be selected and used at suitable intensities so as to achieve low kinetic energy drops. They showed that out of three systems tested in the Ivory Coast, only one produced lower kinetic energy than natural rain. Also, since antecedent water content affects surface crusting, it is best to irrigate soil already wet (i.e. use low intensity initially, increase intensity later).

B. Chemical Soil Management

1. Use of gypsum/phosphogypsum

The management of irrigation water of poor quality is a complex problem and beyond the scope of this review. Gypsum/phosphogypsum is a much vaunted ameliorant to use when sodicity is high or electrolyte concentration is very low. Much research has been done in this regard, particularly in South Africa and Egypt, often with spectacular results (Wahdan and Abou-Hussein, 1977; El-Amir et al., 1986; Levy et al., 1988a; 1988b; Harmse and Nel, 1990; Levy and van der Watt, 1990; Smith, 1990; van der Watt and Claassens, 1990; Stern, 1991; van der Watt and Claassens, 1991). Various aspects of this work has already been referred to above. In Africa, an important consideration will always be the economics of using a chemical ameliorant, and the benefits will have to be demonstrated by prior experimentation.

2. Use of soil conditioners

There is no doubt about the ability of synthetic soil conditioners to create stable aggregates. Where only the top few millimeters of soil is involved, the quantities required become less. Currently several groups in South Africa are involved in research in this area. For example, Laker (1991) has shown that a humic substance derived from the oxidation of coal is capable of stabilizing soil aggregates and improving infiltration rates on a very dispersive soil. The coal-derived substances being tested will be much cheaper than conventional soil conditioners, which makes their use under particular conditions more attractive.

Soil conditioners have also been used to reduce evaporation from the soil surface. In this case, the materials are used to establish a surface seal. Polyacrylamide (PAM) (El-Amir et al., 1986), bitumen and urea formaldehyde (Stradiot et al., 1986) were shown to be effective in this regard.

VII. Conclusions

The volume and quality of research on soil crusting that has been done on the very large African continent reflect an awareness of and the gravity of the problem. Very often soil crusting is directly related to problems such as soil water regimes, runoff and erosion. In many areas, human influences result in intensive and even excessive pressure on soil resources. The exact contribution of crusting per se to soil degradation in Africa is difficult to establish, but undoubtedly is of great importance.

Sufficient knowledge and technology is available to effectively combat the problem in most cases. However, in many parts of Africa transfer of knowledge and technology are inadequate and the means of farmers limited for the successful implementation of effective management systems.

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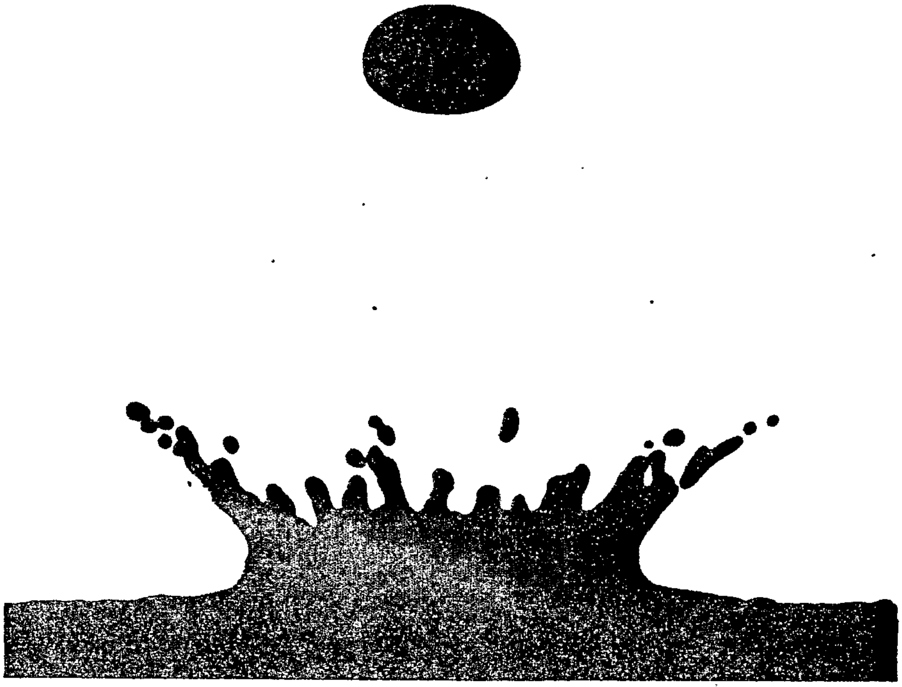

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