SEALING, CRUSTING AND HARDSETTING SOILS IN SAHELIAN AGRICULTURE

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A presentation of the Sahelian environment is given adopting a pedological approach. Soils, parent materials and soil forming factors are considered with respect to crusting hazards. Soil classification and structural stability tests are evaluated as possible aids to diagnosing the risks and analysing the factors involved in crusting processes. The Sahelian classification system of surface crusts is outlined along with its applications in the areas of mapping, remote sensing, hydrological and ecological modelling.

INTRODUCTION

The 17-year drought that began in 1968 in West Africa played a major role in bringing world attention to the Sahel region. Some 25 million people faced famine and disease as well as social and economic disruption. Production from grazing and rainfed cultivation lands suffered severe losses due to a marked downward trend in annual rainfall, associated with the encroachment of the Sahara desert. From a soil point of view, desertification appears as linked to physical degradation (Valentin and Casenave, 1990) including sealing, crusting, hardsetting, and eventually wind and water erosion, as it is to chemical alteration (e.g., salinization and alkalinization). In particular, surface crusts in the region have considerably extended over the last twenty years (Gavaud, 1989).

The significance of surface crusts for Sahelian agro-ecology has been recognised for more than 40 years (Aubert and Maignien, 1948) and schematically three major series of studies have been carried out since then, each corresponding to a specific approach. The first phase, in the 1960s, mainly focused on the determination of structural stability of disturbed samples. The main objective was to relate the vulnerability to structural degradation of soils being surveyed or tested for cultivation techniques to structural degradation (Pias, 1970; Charreau and Nicou, 1971; Boulet, 1974; Gavaud, 1975). The second phase consisted in studying crusting processes in the field using rainfall simulation, in connection with runoff and erosion studies (Casenave and Valentin, 1989). Although the first two phases are still in progress, a third phase can now be identified with the emergence of remote sensing studies on the reflectance of surface crusts (Mougenot and Zante, 1986; Courault *et al.* 1991). Van der Watt and Valentin (1992) have recently reviewed the major factors affecting crust formation, the consequences of soil crusting and the management methods to combat sealing and crusting in Africa.

"Seal" is the term generally given to a wet crust. Considering that forming processes and features are the same for both "seal" and "crust" (Valentin and Bresson, 1992), no further distinction will be made in this article where "crust" will be preferred. Hardsetting is not a widely-used term outside Australia although this phenomenon occurs in may soils in the world. The most recent definition has been given by Mullins *et al.* (1990): "Hardsetting soils are soils that set to a hard, structureless mass during drying and are thereafter difficult to cultivate until the profile is rewetted".

DEFINITION AND GEOGRAPHICAL EXTENT OF THE SAHEL

The term "Sahel" (Chevalier, 1900) is derived from an Arabic word (Sahil) signifying a coast or a flat land. It denotes the southern fringe of the Sahara adjoining the moist savanna. Its limits are ill-defined being based upon either rainfall amount, length of the rainy season, vegetation type, hydrological patterns or latitude.

The most commonly accepted northern limit is the 100-mm isohyet (Le Houérou and Popov, 1981) which is approximately the line separating the contracted and the scattered perennial vegetations. However, the rainfall amount that delineates the southern limit varies more substantially: from 60 mm - with the occurrence of the woodland savannas - to 850 mm (Casenave and Valentin, 1989). In its broader delineation, the Sahel can be divided into four subclimatic zones: very arid or northern Sahelian (100-200 mm), arid or central Sahelian (200-400 mm), semi-arid or southern Sahelian, (400-600 mm), and dry humid or Sudano-Sahelian (600-800 mm). In this article we refer principally to the zone lying between 200 and 600 mm of mean annual rainfall, i.e. roughly between latitude 13° and 16°N. Burkina Faso, Nigeria and Cameroon.

SOIL FORMING FACTORS

Parent Material

Three major groups of parent materials can be identified in the Sahel: (i) the rocks of the Precambrian Basement Complex (including granites, gneiss, schists and, to a lesser extent, basic intrusions); (ii) Sedimentary rocks (sandstones, alluvial and lacustrine sediments); (iii) aeolian deposits (sand and silt). Precambrian rocks belong to the stable West African craton. These formations are exposed mainly in the southern Sahel and in the Sudano-Sahelian zone.

In the Sahel proper, they are covered by more recent sedimentary rocks belonging to four main basins: the Taoudeni basin in Mali and western Burkina Faso from the Primary era; the Niger basin in Niger and Mali from the Secondary and Tertiary eras (including Continental Terminal); the coastal basin in Mauritania and Senegal from the same eras; and the Lake Chad basin. Unlike northern Africa, silt deposits (loess) are nearly absent and seem confined to northern Nigeria (Zonneveld *et al.* 1971). No formation consisting of aeolian clay deposits, comparable to "parna" in Australia, has been identified.

Dust Deposition

Even though thick formations of fine aeolian materials are virtually absent, dust deposition may play a significant role. In particular, windborne dust might favour surface crusting (Valentin, 1981). In northern Nigeria, Möberg *et al.* (1991) recorded at six locations during one dry season an average dustfall of 580 kg ha^{-1}. Clay and silt constituted 25% of the dust; the rest was very fine sand. The dust had higher pH and cation exchange capacity, and contained more extractable phosphorus, organic matter and exchangeable cations and less extractable Al and exchangeable acidity than the samples from eight soil profiles with which it was compared. The dust also had a higher content of 2:1 layer silicate clay minerals and lower amounts of Fe-oxyhydroxides than the soil samples.

Climate

Rainfall. In the Sahelian zone of West Africa, rainfall distribution is mono-modal with rains falling from June to September, showing a rather steady peak in August, and the rest of the year remaining virtually dry. The North-South mean annual rainfall gradient is about 1 mm km^{-1} in latitude (Le Houérou, 1976).

However, another dominant feature of the Sahelian climate is the high temporal and spatial variability of precipitation. this variability increases with aridity. The coefficient of variation of annual rainfall ranges from 25% in the sudano-Sahelian zone to 80% in the northern Sahelian zone (Le Houérou, 1989). the local variability may also be substantial.

Storms are frequently violent in nature. In Niamey (Niger), 40% of the annual rain falls with an intensity of 50 mm h^{-1} or higher and 20% is over 100 mm h^{-1} (Hoogmoed, 1986). Roose (1973) estimated that the rainfall erosion index R of the USLE could be simply obtained by dividing the mean annual rainfall amount by 2. The value of R, expressed with American units, should vary therefore from 300 in the south to 100 in the north.

Droughts. The recent drought has resulted in a southward shift of the isohyets, particularly in the already driest zone (nearly 500 km for the 100-mm isohyet and 100 km for the 1000-mm isohyet). Locally, this is reflected by a decrease of 30-40% in rainfall in the Sahelian proper. Paradoxically, runoff recorded from small watersheds increased during the drought period due to the degradation of the soil surface conditions (Albergel, 1987a; 1987b).

Long dry periods extended over the whole Sahel several times in the past, in 1911-1916 and 1940-1946. However, neither of these droughts reached the duration and intensity that the region experienced in the 1970s and 1980s. Persisting ndroughts occurred in the 15th, 16th, 18th and 19th centuries (Maley, 1981). Geological evidence indicates that the region was repeatedly subject to change during the late Quaternary. Notably the Sahara encroached with wind-driven sand far southwards between 20 000 and 12 000 years B.P.

Temperatures. The Sahel is probably one of the hottest broad ecological regions, even hotter than the Sahara (Le Houérou, 1989). A mean annual temperature of 30°C is reached in many weather stations between 14 and 16°N. The mean annual minimum is 18-20°C and the mean maximum 35-38°C. The coldest month is January when the mean monthly minimum drops to 10-15°C and the absolute minimum to 0°C or even below in the northern Sahel. The mean monthly maximum is recorded in May with absolute maximum rising above 50°C in the fringe of the Sahara.

Wind. Two wind regimes occur: from November to April, the dry harmattan wind blows from the north-east and east while from May to October, the monsoon regime brings humid winds from the south-west and west. The mean annual and monthly wind speeds are relatively low (2-4 m s^{-1}). Maximum wind velocity is generally recorded in June when dust storms are favoured by uncovered soils. A maximum speed of 110 km h^{-1} was recorded in northern Nigeria (Kowal and Kassam, 1978).

Potential evapotranspiration. PET in the Sahel ranges from less than 1800 mm yr^{-1} in the south to over 2200 in the north (Le Houérou, 1989).

Topography

The elevation rarely exceeds 400 m above sea level. As a whole, the region is flat. Five geomorphic elements can be distinguished.

Hills and inselbergs. Hard rocks of the Pre-Cambrian which form low hills and inselbergs in small areas. Their general direction is from north-east to south-west.

Plateaux. The landscape is often dominated by broad, ironstone plateaux with or without discontinuous sand cover. These armoured plateaux are associated with the oldest soils.

Valley systems. Long slopes (1-4 km) with gentle gradients (<4°) lead to sand-filled stream beds, or broad sand plains. The sands result from a combination of aeolian, colluvial and fluvial processes.

Sand dunes. The main geomorphological features are the Pleistocene sand dunes. These stabilised and vegetated dunes and sand sheets occur in regions with as much as 750 mm rainfall. These dunes have slopes typically less than 3°.

Plains and lacustrine regions. Large flat and ephemerally flooded plains occur in the inland delta of the Niger river in Mali and in the southern areas of Lake Chad basin.

Vegetation

Vegetation zones follow climatic zones : grass savanna (or referred to as "steppe") in the northern Sahel, Mimosaceae savanna with an annual grass layer in the central Sahel; Combretaceae savanna with an annual grass layer in the southern Sahel; and Combretaceae savanna and woodland with a perennial grass layer in the Sudano-Sahelian zone (Le Houérou, 1989). Since most of the aerial part of the grass is generally eaten by grazing animals (and/or burnt in the wettest zones), it is mainly the decay of roots which forms organic matter in Sahelian soils.

Soil Fauna

Faunal activity is dominated by termites. Fungus-growing termites like *Cubitermes* develop on seasonally waterlogged iron-capped plateaux. In small depressions of northern Senegal, Lepage (1974) observed that *Bellicositermes bellicosus* may ingest as much as 50% of the annual grass production, hence there is a pronounced reduction in soil cover and increased hazard of surface crusting. Likewise, erosion of the cathedral-shaped nests of species like *Bellicotermes*, *Macrotermes* and *Odontotermes* may cause crusting of a ring around the termite mounds (Clos-Arceduc, 1956; Zonneveld *et al.* 1971). Many crusted sites, particularly on sandy soils, result from these mound-building termites which bring fine material from deep layers, 40-55 m in northern Senegal (Lepage *et al.* 1974), to the surface. Many clay rich sites are thus possibly sites of old termite mounds. On the other hand, these termites perforate the soil surface to build surface galleries (Chase and Boudouresque, 1989). The occurrence of tunnels at the soil surface are an indicator of high infiltrability (Casenave and Valentin, 1989; 1992). Furthermore, termites are generally considered to increase deep soil porosity. Biochannels encourage water infiltration and facilitate root development. Similarly, earthworm burrowing increases soil porosity. Moreover, given that their casts are generally highly resistant to slaking, they form stable aggregates (Blanchard, 1990). They also redistribute organic matter in the profile. However, in the Sahelian zone, such beneficial effects of earthworms are restricted to narrow riparian strips.

Human Activity

Pastoralism. Apart from some limited lowlands which profit from water run-on from crusted slopes, as in the Ader Doutchi region in Niger, arable farming is not viable in regions with < 350 mm $year^{-1}$ rainfall. In such areas, human activity is based on cattle in a nomadic herd system. The influence of grazing on soils is closely linked to the effects of cattle. Depending on the texture of the soil, trampling may favour (loamy soils) or impede (sandy soils) surface crusting (Valentin, 1985). Overgrazing exposes the soil surface to rain impact, and thus to crusting and erosion hazards (Leprun, 1978). On the other hand, dung tends to increase organic matter content and locally enhance surface structure.

Rainfed agriculture. The impact of cropping on soils depends largely on the climatic zone and population pressure. Two main groups can be distinguished: (1) "Traditional" systems where density of population is still relatively low. This is generally the case in the drier zone (350-650 mm) where mainly Pearl millet (*Pennisetum glaucum* (L.) R.Br), often intercropped with cowpea (*Vigna unguiculata*), is grown. Shifting cultivation is based on a long fallow period (>20 years). Fallowing restores soil structure and chemical fertility (Charreau and Nicou, 1971; Valentin and Janeau, 1989). The restoration of physical properties may be hampered when chemical fertility has been too depleted by cropping and/or when the soil has been badly compacted (Seyni-Boukar, 1990). (2) Transitional systems where higher population densities increase pressure on the land. They occur in wetter zones (southern Sahel and Sudano-Sahelian zones) where sorghum (*Sorghum bicolor* (L.) Moench) and cotton can be grown. Fallowing is shortened, if not suppressed. Organic matter content drops dramatically under prolonged cultivation, more so in fine-textured soils than in sandy soils (Feller *et al.* 1989). This loss of organic matter leads to unstable clods and thus to increased crusting problems (Albergel and Valentin, 1988). In the most evolved systems, animal traction has been adopted to some extent (in Senegal, Mali and Burkina Faso) as well as low-inputs of fertilisers and herbicide especially where cotton is grown.

Irrigated agriculture. Despite the great amount of available water from the rivers and from the numerous and large aquifers, irrigation remains a rare practice in the Sahel. Besides economic, health and cultural obstacles, water available for irrigation is rarely suitable for the maintenance of surface structure, not to mention the major risks of salinization especially in the absence of efficient drainage systems (Cheverry, 1966; Valet, 1990).

MAIN SAHELIAN SOILS

One of the major features of the soils in the Sahel and the Sudano-Sahelian zone is their low silt content (<10%). In the Sahel proper, most soils are sandy (clay + silt <20%), slightly acidic (6<pH<6.5) and low in organic matter (<1%), nitrogen (0.02-0.03%) and available phosphorus (4-6 ppm). They are classed as Cambic and Luvic Arenosols in the FAO/UNESCO soil classification and referred to as Psamments and Aridisols in the US Soil Taxonomy. Most sandy topsoils develop in aeolian deposits and may result from vertical and lateral eluviation. Soils often occur in well defined catenas (Boulet, 1974). Sandy, well drained, leached and eluviated soils occur upslope. Downslope, water, clay and bases accumulate in poorly drained soils so that new minerals can be formed (principally active clay). Upland soils contain a high percentage of gravel. Unlike other arid and semi-arid zones, saline and alkaline soils are limited in extent. They mainly occur in the vicinity of Lake Chad and a few smaller lakes (Horo and Faguibine in Mali, Fitri in Chad).

DIAGNOSIS OF STRUCTURAL DEGRADATION

Soil science literature is rich in papers reviewing stability tests (e.g., Hamblin, 1980; Loch, 1989) and comparing them (e.g., De Vleeschauwer *et al.* 1978; Churchman and Tate, 1986; Matkins and Smart, 1987; Valentin and Janeau, 1989; Wace and Hignett, 1991).

The aggregate stability test proposed by Hénin *et al.* (1958) is the most commonly used in French speaking countries of the Sahelian zone. The procedure consists of submitting air dried samples to three different treatments: ethanol (to test wet cohesion), benzene (to test wettability), and distilled water. After standard shaking and sieving the amount of 'stable' aggregates remaining on the 200μm sieve is determined for the different treatments and also the amount of clay and silt fraction (<20μm) that remain in suspension (to test clay+silt dispersability). The instability index (Is) is then calculated as follows:

$$Is = \frac{(\%<20um)}{\frac{Ag_a + Ag_b + Ag_c}{3} - 0.9\ (\%>200um)}$$

where:

Ag_a: % stable aggregates after the ethanol pre-treatment

Ag_b: % stable aggregates after the benzene pre-treatment

Ag_c: % stable aggregates after the water pre-treatment

The major contribution of this method to crusting studies is in the analysis of the impact of intrinsic soil factors on crusting. Soil structural stability was shown to decrease with decreasing clay content (Pieri, 1989). This test was also employed to investigate the role of the content and nature of organic matter in stabilising the soil structure (Combeau and Quantin, 1964; Charreau and Nicou, 1971). Recently, Durtartre *et al.* (1993) showed that aggregate stability of sandy soils from Burkina Faso and Mali was enhanced when organic matter included humin and uronic acid related to microbial activity. The test of Hénin *et al.* (1958) was sensitive enough to monitor the aggregate stability decline under cultivation and increase under fallow (Combeau and Quantin, 1963). Damour and Killian (1967) found that better aggregate stability was obtained with *Graminea* compared to plants with taproots and rhizomes.

Furthermore, experiments conducted on fodder crops in the Central African Republic indicated that *Pennisetum purpureum* or *Panicum maximum* resulted in aggregate stability recovery to the same level as that under natural savannah within only four years. Conversely, no improvement was observed with *Stylosanthes gracilis* and *Pueraria javanica* even after six years (Morel and Quantin, 1964; 1972).

The test of Hénin *et al.* (1958) also revealed a seasonal variation in aggregate stability, linked to hydrophobic properties related to organic matter. In dry periods, hydrophoby of organic compounds increases (Sebillotte, 1968; Boiffin, 1976) and reduces the rate of wetting of dry aggregates, hence reducing slaking. Aggregate stability is therefore subject to seasonal variations and reaches a maximum at the end of the dry season (Combeau and Quantin, 1963). Significant correlations have also been established between the instability index and soil losses from field runoff plots (Quantin and Combeau, 1962a) and laboratory rainfall tests (De Vleeschauwer *et al.* 1978). The test of Hénin *et al.* (1958), along with that of De Leenheer and De Boodt (1959), was found to be the most relevant to predict erodibility in Nigeria among the 14 indices tested (De Vleeshauwer *et al.* 1978). Also a significant relationship was found between aggregate stability and cotton production (Combeau *et al.* 1961). Moreover, Dabin (1962) established a significant correlation between rice production in Niger, and an index based upon this aggregate stability index (Is), soil porosity and available soil moisture.

However, such approaches using aggregate stability tests are now felt to be unsatisfactory (Francis and Cruse, 1983; Le Bissonnais, 1988; 1990; Webb and Coughlan, 1989; Loch, 1989; Dickson *et al.* 1991; Rasiah *et al.* 1992). Among the criticisms which have been put forward, the most serious ones are:

- *The pre-wetting techniques:* Since aggregates are strongly susceptible to slaking when dry (Yoder, 1936) disaggregation depends on initial soil water content. Thus, using dry conditions favours shattering. Under initial wet conditions, classification is usually more discriminatory due to the mechanical disaggregation (especially if the sample is shaken) as shown by Le Bissonnais (1988), but may largely differ from the screening of soils derived from tests conducted under dry initial conditions (Fig. 1). Classification of soil according to these tests therefore depends upon the initial moisture of the aggregates and the rate of wetting.

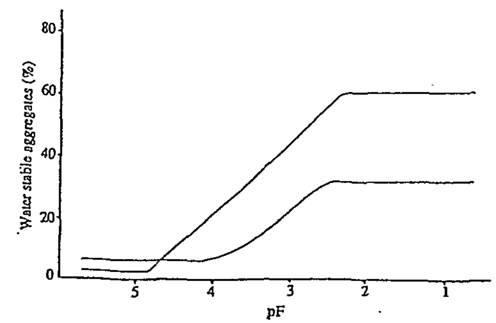

Fig.1. The influence of the initial moisture tension of aggregates before immersion in water when testing for structural instability. The aggregates are more stable when initially wet and the classification of the two soils depends upon the initial moisture conditions (adapted from Le Bissonnais, 1988).

- *The relevance to field conditions:* Considering intrinsic soil factors irrespective of moisture conditions may be misleading when predicting crusting hazards in the field. As a corollary to the previous criticism, two soils ranked with the same structural stability index can be subjected to crusting processes the severity and the intensity of which may differ largely depending upon prevailing field moisture conditions. Moreover, when the aim is to predict the behaviour of soil under rain, attempts to reproduce in the laboratory the disruptive forces of natural raindrop impacts, by shaking, ultrasonic disruption, remoulding or simulating single water drops, leave much to be desired. Under field conditions, a range of drop sizes is applied to a range of aggregate sizes.

Therefore, the most relevant method of wetting the soil is to apply simulated rain with an intensity and a drop-energy distribution similar to the natural rainfall (Loch, 1989).

Various aggregate stability indices were evaluated on 20 wet savannah soils of Côte d'Ivoire as predictors of actual crusting determined in the field under rainfall simulation (Valentin and Janeau, 1989). It appeared that no unique index could be used to predict surface crusting since processes were interrelated with the antecedent moisture conditions and the rainfall patterns. The authors concluded that the use of the index of Hénin *et al.* (1958) should be restricted to the assessment of crustability where the soil dries before the next shower, as in the Sahel, since it includes a sudden wetting of predried aggregates. Where moist soils are submitted to less aggressive rainfall, a consistency index, like Atterberg's liquid limit, seems better adapted.

Useful as they are, these tests are no substitute for the monitoring of structural degradation *in situ*. In this respect, field rainfall simulation has proved an invaluable method for screening soils rapidly to establish the stability of soil aggregates under various conditions and the permeability of the crusts once formed (Wace and Hignett, 1991). Three types of rainfall simulators have been used in the Sahelian zone. A rotating-boom simulator capable of irrigating 200 m² was used in northern Burkina Faso and in southern Niger (Collinet and Valentin, 1979; 1984; Collinet, 1988a; 1998b). A rotating-disk rainfall simulator (Morin *et al.* 1967) was employed in Mali and Niger (Hoogmoed and Stroosnijder, 1984; Hoogmoed, 1986). Oscillating-nozzle sprinkling infiltrometers (Asseline and Valentin, 1978) were constructed and extensively used for surface crust studies (Casenave and Valentin, 1989; 1992), in northern Niger (Valentin, 1981; 1991), in Burkina Faso (Chevallier and Valentin, 1984; Albergel *et al.* 1986; Albergel, 1987a; 1987b), in northern Cameroon (Pontanier *et al.* 1986; Thebe, 1987; Seyni-Boukar, 1990; Seyni-Boukar *et al.* 1992), in Mali (Albergel *et al.* 1991), and in Senegal (Albergel *et al.* 1992; Touma and Albergel, 1992).

Concerning the influence of texture, a discrepancy was found between results from the test of Hénin *et al.* (1958) and field rainfall simulation tests. Results obtained in Mali (Hoogmoed, 1986) and in Niger (Valentin 1981; 1986b; 1991; Hoogmoed, 1986) suggest that the texture most prone to crusting consisted of approximately 90% sand and 10% silt or clay. These field results were corroborated in the laboratory by Poesen (1986). With higher sand content, the amount of fine particle is apparently not sufficient to clog the pores. Collinet (1988a; 1988b) observed that smectite and illite favour crusting while kaolinite makes the soils more stable. When the clay consists of 2:1 clay minerals, crusting problems increase exponentially with increasing clay content up to a threshold of about 18% clay above which they improve stability (Nicou and Charreau, 1980). This effect needs to be balanced by the organic content. In Niger, Valentin (1991) described severe crusting processes in a soil containing 34% clay (mostly montmorillonite) and only 0.7% O.M.

One must therefore be aware that texture should not be considered separately from the organic matter content. Minor increases in organic matter content may have a more beneficial effect upon structural stability of sandy soils than a higher increase in finer textured soils. Considering the ratio:

$$S = \frac{\textit{Organic matter content } (\%) \times 100}{\textit{Clay } (\%) + \textit{Silt } (\%)}$$

for numerous savannah soils of West Africa, Pieri (1989) distinguished the following critical values of S :

$S < 5$	severe physical degradation,
$5 < S < 7$	high hazards of physical degradation,
$7 < S < 9$	low hazards of physical degradation,
$9 < S$	no physical degradation

High amounts of iron are generally associated with greater resistance to slaking under rainfall (Farres, 1987). The detrimental influence of low organic matter contents can be therefore offset at least partly, by the presence of a high quantity of iron as was shown by Obi *et al.* (1989) in Nigeria. The Chroma values from the Munsell chart seem to be an interesting indicator of susceptibility to crusting, suggesting that hematite has a more pronounced stabilising effect than goethite (Valentin and Janeau, 1989). Likewise, rainfall simulation tests showed that Sahelian soils are more prone to crusting when Mg/CEC is greater than 50% (Collinet, 1988a).

SAHELIAN TYPES OF SURFACE CRUSTS, PROCESSES AND PROPERTIES

Two main types of crusts are generally distinguished by their mechanisms of formation (Chen *et al.* 1980): structural crusts and depositional crusts. The former develop *in situ* whereas the latter are formed from particles that have been transported over a certain distance from their original location where they were detached. Detailed studies in West Africa (Casenave and Valentin, 1989; Valentin, 1991; Valentin and Bresson, 1992) indicated that a wider range of surface crusts could be identified in the Sahel, and resulted in a more comprehensive classification.

Structural Crusts

Depending on the texture of the top layer, two main types of structural crusts commonly occur (Valentin and Bresson, 1992; Bresson and Valentin, 1994). The first type, *slaking crusts*, consist of one layer made of fine particles with residual roughness due to remnants of initial clods. Slaking crusts develop only when soils contain enough clay (>15-20%) to entrap and compress air during wetting so that aggregates shatter. Processes can also involve concurrent swelling due to the expansion of the clay lattices (Valentin, 1991). Similarly, oversaturation of the uppermost mm of the soil (Collinet, 1988a) tends to turn the dispersed clayey materials into slush which fills the interstices. Since slaking is associated with the wetting of dry soils, it must be emphasised that the resulting crusts can develop independently from impact energy, for instance, under a protecting mulch (Valentin and Ruiz Figueroa, 1987) or under furrow irrigation (Valet, 1990).

The porosity of the remaining clods embedded in the slaking crusts remains generally higher than the depressions where depositional crusts form (Falayi and Bouma, 1975; Valentin, 1981; Levy *et al.* 1988; Valentin, 1991). Wetting and subsequent slaking produce large amounts of dispersed clay and disjuncted particles. The size distribution of these particles depends on the antecedent soil moisture and the rainfall characteristics (Loch, 1989; Le Bissonnais, 1990). These sediments are susceptible to removal by overland flow. However, during the incipient stages, even though detachment might be high, the possibility of transport remains low due to surface roughness and depression storage. In the following stage, microtopography due to the remaining clods is decreased. The smooth surface favours runoff with higher velocity and shallower depth sheet flow. Since the crust is already formed and compacted, detachment is lower but the high carrying capacity of overland flow is capable of removing and exporting the particles which have been detached and accumulated during the first stage. Consequently erosion may be very high. In the Sahelian zone, slaking crusts develop mainly under tilled conditions at the onset of the rainy season and rapidly evolve into an erosion crust (described later).

The second type of structural crusts, *sieving crusts*, consist of a layer of loose sand overlaying a thin, dense and hard layer of fine material. In its most advanced form, the crust can consist of three well-sorted layers. The uppermost layer is composed of loose, coarse sand; the middle one consists of fine, densely packed grains with vesicular pores; and the lower layer shows a higher content of fine particles with considerably reduced porosity. This type of crusting mainly affects sandy soils and sandy-loams. The well-defined textural differentiation results from a sieving process. Raindrop impact forms micro-craters, the walls of which present a clear, vertical sorting of particles (Valentin, 1986b). Moreover, percolating water may enhance the downward movement of clay through the upper sandy layers.

Clay particles can accumulate due to entrapped air within the underlying layers during infiltration (Collinet, 1988a; 1988b). The lower fine-textured layer is responsible for the low infiltrability of such crusts (0-15 mm h^{-1}; Casenave and Valentin, 1989; 1992). Loose particles of the sandy micro-layers of the sieving structural crusts can be readily removed by wind and runoff. Wind-drifted sands are entrapped by surrounding vegetation and can evolve in turn into sieving structural crusts if vegetation decays due to drought and/or overgrazing (Valentin, 1985).. These sieving crusts, also referred to as "filtration pavements" or "layered structural crusts", have been recognised under a variety of conditions: in untilled soils from northern Sahel to the Sudano-Guinean zone (Valentin and Janeau, 1989), in tilled soils from northern Sahel (Valentin, 1981) to coastal wet tropical regions in Côte d'Ivoire (Hartmann, 1991) and in Togo (Poss *et al.* 1991) as well as in West African urban environments (Bouvier, 1990). On some recent dunes, almost devoid of fine particles, aeolian deposited sand forms laminated crusts, referred to as *aeolian crusts* which are notably more pervious than sieving crusts (Casenave and Valentin, 1989).

A singular form of sieving crust is the *pavement crust* where coarse fragments are embedded in a crust the microstructure of which is very similar to the sieving crust with three layers. Vesicular porosity is more pronounced, especially below the coarse fragments. Infiltrability is extremely low (0-2 mm h^{-1}; Casenave and Valentin, 1989, 1992) and decreases when the size of the coarse fragments increases (Valentin and Casenave, 1992). However, these pavement crusts tend to protect the soil underneath, playing the role of a mulch, and thereby limit further erosion (Collinet and Valentin, 1979, 1984; Casta *et al.* 1989). These very impervious crusts occur mainly in the desert and in the Sahel. In the Sahara, this surface condition is named desert pavement or "Reg", "Serir", "Tanezrouft", or "Tenere". When the substratum is a hard rock surface or flagstones (e.g., limestones, sandstones, basalt), it is called "Hammada" (Le Houérou, 1989). In Sudanian regions (800-1200 mm of annual rainfall), small gravel originates from dismantled iron-pans and remains generally free at the soil surface, i.e. not embedded in a pavement crust. They favour water intake and limit erosion (Collinet and Valentin, 1979; Valentin and Casenave; 1992). On gravely kaolinitic soils, soil tillage increases gravel on the surface and can reduce surface crusting (Casta *et al.* 1989).

Erosion Crusts

Most crusting problems in the Sahel are caused by erosion crusts (Aubert and Maignien, 1948; Audry and Rossetti, 1962; Leprun, 1978; Hoogmoed, 1986; Chase and Boudouresque, 1989; Gavaud, 1989; Tauer and Humborg, 1993). Indeed, erosion crusts form conspicuous barren patches of land well-known to West-African farmers or pastoralists who termed them "zipelle" or "vuigo" in Central Burkina Faso (respectively "white soil" or "glade" in More), "gangani" in western Niger (in Djarma), "ako" in southern Niger and northern Nigeria (in Haussa), "harde" in northern Cameroon (in Foulani), and "naga" in Chad (in Arabic). The erosion crusts consist of a smooth hard layer formed from fine particles. Porosity is restricted to a few cracks and vesicles so that infiltrability is very low (0-2 mm h^{-1}; Casenave and Valentin, 1989; 1992) as is evaporation (1-2 mm day^{-1}; Le Fevre, 1993).

Erosion crusts derive from the two already-mentioned forms of structural crusts. They are slaking structural crusts which have became smooth and relatively enriched in fine particles. They can also be formed from sieving crusts from which the loose sandy layers have been removed by either overland water flow or more commonly by wind (Valentin, 1985). Barren spots capped with an erosion crust are therefore commonly surrounded by sandy aeolian micromounds (Aubert and Maignien, 1948; Valentin, 1985). Once formed, these crusts promote runoff and downhill erosion but are resistant to wind and water erosion compared to sieving crusts. Erosion crusts cannot usually be colonised by vegetation because of their resistance to seedling emergence, the very dry pedoclimate they produce, and primarily because seeds that deposit on the soil surface are invariably removed by wind and overland flow. Such processes favour the expansion of these crusted patches under drying, (and/or overgrazed) conditions. This process has been regarded as "sahelization" by Albergel and Valentin (1988) to indicate the occurrence of such a typical Sahelian feature within desertified Sudanian degraded areas as a result of drought and/or a shortened fallow system. When rainfall returns to a wetter regime, microdunes tend to erode. Sandy sediments cover the erosion crusts and trap seeds. Consequently, vegetation can recover, trapping airborne sand and gradually burying the erosion crusts (Valentin, 1985).

Depositional Crusts

Most depositional crusts are a combination of runoff and still water depositional crusts (Valentin and Bresson, 1992). *Runoff depositional crusts* are characterised by alternate thin layers of contrasting texture. These crusts can be rather thick (up to a few cm) especially when they develop between two ridges or under furrow irrigation. Almost invariably, they overly structural crusts with sharp boundaries (Boiffin and Bresson, 1987; Bresson and Boiffin, 1990). As mentioned previously, their infiltrability is notably lower than that of slaking crusts. *Still water depositional crusts* form in standing water. They consist of densely packed and well-sorted particles, the size of which progressively increases with depth. The vertical particle size distribution, with coarser particles at the bottom and finer particles at the top, is the reverse of that observed in the sieving crusts. Infiltrability is low (0-7 mm h^{-1}; Casenave and Valentin, 1989, 1992). During drying, cracks and curling up plates can develop owing to the difference in shrinkage forces among the microlayers. Such processes favour seedling emergence.

Microphytic Crusts

Surface crusts which exhibit a fine-textured upper layer, e.g., slaking crusts, erosion crusts and still depositional crusts, may be colonised by microphytes as observed in Mauritania (Barbey and Couté, 1976), in Mali (Rietveld, 1978), in Niger (Valentin, 1981) and in Chad (Dulieu *et al.* (1977). These microphytes (mainly algae) can locally strengthen the pre-existing crusts, protecting them from further erosion. Some microphytic crusts form pedestal features contrasting with the surrounding uncolonised and eroded crusts (Casenave and Valentin, 1989). These microphytes are thought to be responsible for the low infiltrability of crusted sandy soils because of their hydrophoby. However, the physical binding effect of hyphae is of higher importance to infiltration than hydrophoby. It was observed that hydrophoby *per se* often disappears following a variable amount of rainfall, e.g., from a few millimetres in the Sahelian zone (Rietveld, 1978) to a few tenths of millimetres in the rainforest zone (Valentin, unpublished data).

Salty Crusts

Like salty soils, salty crusts are rather negligible in extent in West Africa and occur mainly where high amounts of salts are found near the surface, namely near the ocean or in the vicinity of lakes. The animals lick the ground in some specific locations. For a few days, they stay in these so-called "salt cures" for their annual supply of minerals (Leprun, 1978). An array of minerals are found in such crusts. One can distinguish the white saline crusts, which mainly consist of sodium and magnesium chlorides and sulphates. They are usually affected by wind erosion when they dry up. The black saline crusts combine sodium carbonate to organic matter (Aubert, 1976). Some yellow saline crusts may develop on very acid sulphate soils, like those studied by Le Brusq *et al.* (1987) in the Sine Saloum, Senegal. They are composed of aluminium, iron and magnesium sulphates. Sulphate crusts are generally the least porous with low evaporation whilst chloride crusts (formed from NaCl) are the most porous (Galizzi and Peinemann, 1989). White saline crusts were observed in Mauritania (Audry and Rossetti, 1962), in Gourma, Mali (Leprun, 1978); near the shores of Lake Chad, namely in south-eastern Niger (Gavaud, 1975), in northern Cameroon (Brabant and Gavaud, 1985) and in Chad (Pias, 1970). Since most of these soils are clayey and sedimentary, these crusts are rather similar to still water depositional crusts, with polygonally shaped cracks. However, these crusts can evolve in the dry season into a loose, powdery layer, as observed in northern Senegal (Mougenot, 1983).

EVALUATION OF SOIL CLASSIFICATION AS AN AID TO DIAGNOSIS

As observed by several authors (Collinet, 1988a; Casenave and Valentin, 1989), no satisfying correlation can be established at the detailed scales (up to 1:50 000) between soil type as referred to any soil classification system and its susceptibility to surface crusting. Therefore, specific maps of surface conditions need to be drawn at these scales independently from the existing soil maps (Valentin, 1986a; 1991b). However, at larger scales some broad relationships can be proposed (Table 1). In particular, some frequent combinations between parent material, soils and susceptibility of soils to crusting have been recognised (Casenave and Valentin, 1989).

Table 1. Tentative correlation between soil susceptibility to crusting and certain soil groupings in West Africa as referred to in the FAO/UNESCO classification.

Soil groupings	Susceptibility to soil crusting		
	Low	Medium	High
Acrisols		Ferric, Plinthic	
Alisols		Ferric	
Arenosols		Ferralic	Albic, Luvic
Cambisols	Eutric	Ferralic, Dystric	
Ferralsols		Rhodic	Xanthic, Yermic
Fluvisols			Yermic, Thionic
Gleysols	Mollic, Eutric	Dystric	Thionic
Lixisols			Yermic, Ferric
Luvisols		Vertic	Yermic
Planosols	Mollic		Yermic
Plinthosols		Dystric	
Regosols	Eutric		Dystric
Solonetz			Gleyic, Haplic
Solonchaks			Sodic, Gleyic, Haplic
Vertisols	Haplic	Yermic	

Note that these relationships are approximations and may be wrong in detail.

The nature of parent material may have some impact on soil sensitivity to crusting. Almost all of the soils developed on the rocks of the precambrian basement complex are prone to crusting when they are exposed to raindrops. Soils derived from schists, richer in silt, generally experience more severe crusting problems (Poss and Valentin, 1983) than those originating from gneiss or granite richer in coarse sand (Valentin *et al.* 1990). As observed in northern Cameroon, soils developed on green basic rocks offer a stable structure associated with high infiltrability (20-30 mm h^{-1}; Thebe 1987; Casenave and Valentin, 1989; 1992). Soils derived from alluvial materials are very prone to crusting because their particles have already been sorted (Valentin, 1981; Valentin and Ruiz Figueroa, 1987). Susceptibility to crusting of soils developed on aeolian sand material (dunes) depends on the age of the deposits. Soil crusts mainly develop on old fixed dunes sufficiently enriched in fine particles (clay and silt > 5%).

In a typical self-mulching Vertisol, no crust can be maintained following a cycle of wetting and drying. Gilgai micro-relief and cracks favour infiltration at the beginning of the rainy season. However, soil crusting can affect Vertisols containing sodium or degraded by cultivation.

THE SAHELIAN CLASSIFICATION SYSTEM OF SOIL SURFACE FEATURES

Classification and Mapping

In the Sahelian zone, the extent and the type of surface crusts are key factors controlling overland flow (Collinet and Valentin, 1979; 1984; Hoogmoed and Stroosnijder, 1984). Combined with faunal activity, vegetation cover and surface roughness, these parameters enabled the establishment of a classification of "unit surfaces". Eleven major types of unit surfaces were characterised in terms of genetic, morphological and hydrological properties (Casenave and Valentin, 1989; 1992). Some additional criteria including vegetation cover, texture and surface roughness were used as modifiers, resulting in 26 sub-classes, each one being related to hydrologic properties.

This simple system was satisfactorily validated in 47 plots not included in the sample used for calibration. The Sahelian classification system of soil surface features is increasingly used in the Sahelian zone for research and development purposes (Guillet, 1991; Albergel *et al.* 1992), and has been adapted to Sudanian conditions (Valentin *et al.* 1990).

At a higher level, the combination of these unit surfaces allows a "soil surface unit" to be defined, leading to an original mapping method (Valentin, 1986a; 1991b). At present, in West Africa, 24 maps of surface conditions have been established at 1:50 000.

Watershed and Slope Hydrology

These maps served as a basis for improved watershed hydrological modelling (Chevallier *et al.* 1985; Albergel, 1987a; Casenave and Valentin, 1992). As observed by Connolly *et al.* (1991), runoff parameters from 1-m² rainfall simulator plots appear to be appropriate for modelling runoff in catchments. Extrapolation to the watershed scale gives satisfactory results, particularly in the Sahelian zone, where severe crusting determines infiltration characteristics and induces heavy runoff and where hillslope infiltrability decreases from upslope to downslope. Such an approach is more questionable in the wet-savannah zone where minimum infiltrability occurs midslope (Chevallier and Planchon, 1993). Recognition of surface conditions provides a basis for predicting not only runoff but also possible changes over time due to degradation. For example, in a typical catena of northern Burkina Faso, several units have been delineated and characterised by the percentages of their unit surfaces. Using the hydrological parameters provided by the classification enables the evaluation of the amount of runoff as a function of rainfall amount and initial moisture conditions. As illustrated by Fig. 2 a small rainfall event occurring at the onset of the rainy season generated runoff only in the upper part of the catena whilst overland flow is expected to occur throughout the hillslope in the course of the rainy season. Now, assuming that the surface conditions have been degraded as a result of drought and/or human abuse, water flow from upslope areas dramatically increases, thus promoting severe erosion in the downhill fields. This simple model reflects the actual behaviour of several catenas in northern Burkina Faso (Serpantié *et al.* 1991; Valentin, 1992).

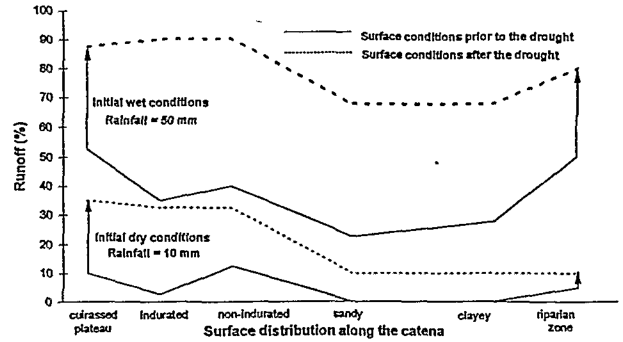

Fig.2. Changes in runoff production under two depths of rainfall and two initial moisture conditions, before and after the degradation of soil surface conditions as modelled along a catena in Burkina Faso (adapted from Valentin and Casenave, 1990).

Soil Water Balance

Owing to the difficulties in estimating runoff, this term is frequently neglected in the common soil water balance equation. What might be admissible in some temperate circumstances leads to substantial errors in the Sahel, where runoff commonly represents 20% of rainfall under cultivated conditions (Roose and Bertrand, 1971). Since the classification system includes 3 types (and 8 sub-types) of cultivated surface features which can occur in succession during the cropping season, the field assessment of these features helps assessing the runoff term in the water balance equation. Using the predicted values of the classification system substantially improves water-balance modelling (Albergel *et al.* 1991; Fig. 3).

Ecological Studies

One of the most striking features of the Sahelian vegetation is the 'tiger bush' (Clos-Arceduc, 1956). This term denotes a pattern of denser perennial vegetation forming 'vegetation arcs' that run close to the contour, hence at right angles to sheetflow. No differences have been observed between deep soils under the vegetation bands and the barren interbands (Ambouta, 1984). The contrast is rather in the soil surface features which control the hydrological processes and the development of this vegetation pattern. Runoff generated on the crusted interbands accumulates and infiltrates in the next downslope band where a thick litter protects the ground beneath. Furthermore, termite activity increases surface porosity. This additional soil moisture facilitates plant colonisation of the leading edge of the arc, hence a continual upslope arc of vegetation across the landscape which is reflected in a space-and-time-sequence: (1) The downslope edge of the band decays as a consequence of decreased moisture conditions too deficient to maintain a dense vegetation cover. Consequently, soil is gradually left unprotected from the beating action of raindrops, hence structural crusts develop and remain unaltered due to termite activity. (2) The removal of the upper sandy layers of the structural crust leads to the expansion of erosion crusts that can be partly ascribed to increased sheet runoff conditions, and partly to the removal of loose surface particles by the wind enhanced by the vegetation collapse. In this latter case, the sandy material is presumably trapped by the surrounding strips of vegetation, hence the observed enrichment in the sand fraction of the vegetated soil. Accelerated erosion exposes the shallow gravel layer so that initial structural and erosion crusts are gradually altered into gravel crusts. Erosion and gravel crusts generate an intense runoff but tend to protect the soil from further degradation provided sheetflow does not concentrate. The gradual accumulation of sediments tend to even the land surface, with sedimentary crusts increasingly covering the erosion and gravel crusts. This silting of small depressions is generated by temporary flooding of bare land. (3) Colonisation of still depositional crusts by grass and by layering pioneer shrubs is greatly fostered by the cracks. Furthermore, this deposition zone intercepts run-on, sediments, and possibly seedlings removed by surface flow or wind from the bare interband. (4) When the distance from the catchment source increases as a consequence of the slow upslope shift of the band, the vegetation decays and the cycle starts again.

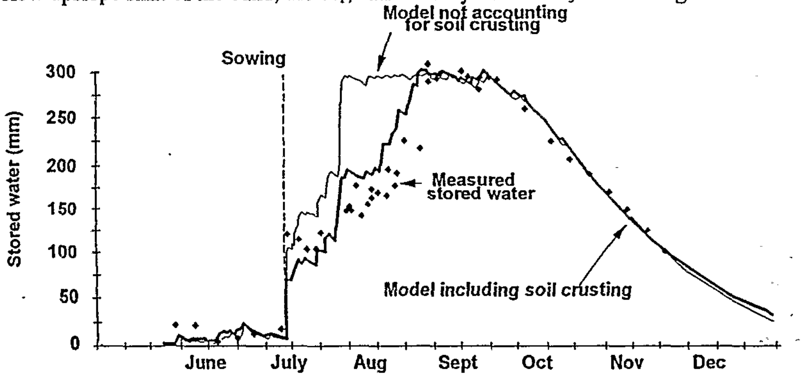

Fig. 3. Water balance of a field cropped with millet in Mali. The prediction of the stored water into the soil is substantially improved when surface crust hydrological parameters are accounted for (adapted from Albergel et al., 1991).

Remote Sensing Applications

A satisfactory relation was found between the Sahelian classification of soil crusts and reflectance (Courault *et al.* 1991). A 1:200 000 map of surface features for the region of Niamey, Niger, was prepared (d'Herbès *et al.* 1992). Such an approach greatly facilitates the studies of long-term dynamics of degradation (Mougenot and Timouk, 1994). The combination of the Sahelian classification system of surface features and remote sensing analysis helps predict the behaviour of ungauged watersheds (Albergel *et al.* 1987). Furthermore, potential areas for runoff farming have been identified in Mali using remote sensing, the volume of available water being estimated from the hydrological parameters of the classification system (Tauer and Humborg, 1993).

HARDSETTING PROBLEMS IN THE SAHEL

When Sahelian soils dry, they frequently harden, hampering tillage and root development (Charreau and Nicou, 1971). In a recent review of northern Cameroon, Lamotte (1993) distinguished three main types of hardsetting soils: (1) Soils with very hard sandy layers that usually occur under a more or less softer sandy layer. Besides their cohesion, the denser layers have higher bulk densities (1.6 to 1.8 compared to 1.4 to 1.5 Mg m^{-3}), a lower annual moisture range (12 to 15% compared to 2 to 20%) and lower permeability when compared to the softer upper layers (Tobias and Vanpraet, 1982). Some indications suggest that these properties could result from the gradual clogging of the pores between sand grains due to newly formed clay. Such a pedological process may be favoured by the succession of drying and wetting periods (Lamotte, 1993). (2) Soils with a very hard clay layer that are thought to be derived from Vertisols degraded by cultivation (Seyni-Boukar *et al.* 1992). These very hard layers, sandy or clayey, are not necessarily associated with a high sodium content (Guis, 1976) but rather with a low iron content, as reflected by their pale colour (Brabant and Gavaud, 1985). (3) The Anthropogenic hardset soils also originate from either trampling close to villages or ponds or from ruined human constructions (Lamotte and Marliac, 1991).

CONCLUSIONS

The West African Sahelian region combines a complex web of climatic, edaphic and human factors that encourage crusting and hardsetting of already poorly productive soils. Despite past identification of these problems, they had been given little attention prior to the 1970s, as soil scientists along with agronomists had to tackle other tasks of higher priority, such as soil mapping and fertilizer tests. These two main lines of research have proven rather insufficient. Soil maps were based mainly on the pedogenetical criteria of deep soil layers not really relevant to predicting actual soil behaviour. Also economic constraints are still restricting the use of fertilizers.

Detailed studies on surface crusting in the region were initiated during the protracted drought of the 1970s when erosion and still water depositional crusts became symptomatic of desertification. Since then an increasing number of scientists and development officers have become aware of the major implications of crusting and hardsetting problems, both in cropped lands and in rangelands.

In particular, the struggle against the extension of erosion crusts, perceived by farmers and pastoralists as a sort of disease that gradually jeopardised the land, has been selected as a priority objective by most non-governmental organisations working in the region. However, a significant effort is needed to bridge the gap between research and management, good will being usually insufficient to efficiently combat such complex problems.

Current research is mainly conducted by ORSTOM (The French Scientific Research Institute for Development through Cooperation) and ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), and to a lesser extent by National Agricultural Research Centres. A variety of aspects are being explored including the genesis of microphytic and erosion crusts, the spatial effects of crusts on overland flow at various scales, their influence on water (rill and interill) and wind erosion, as well as on evaporation. Attempts are also being made to relate soil crusts, colour, reflectance and albedo to feedback effects of drought and soil degradation on possible climatic change. This aspect is a part of the SALT programme (Savanna in the Long Term) which is a core project of I.G.B.P. (International Geosphere Biosphere Program). Another program encompassing a substantial sub-program devoted to structural degradation problems is being implemented in Senegal, Mali, Burkina Faso, Niger and northern Cameroon, on the possible benefits of fallow management on soil restoration.

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