Soil Crusting

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I. Introduction

The term soil crusting refers to the forming processes and the consequences of a thin layer at the soil surface with reduced porosity and high penetration resistance. Surface crusts are largely blamed for initiating runoff, favoring interrill soil erosion and inhibiting seedling emergence. Some authors (after Arndt, 1965a and Remley and Bradford, 1989) distinguished surface sealing, defined as the initial or wetting phase in crust formation, and crusting as the hardening of the surface seal in the subsequent drying phase. Although soil crusting is now recognized as one of the major forms of soil degradation, it has been long confused with its causes (dispersion, ...) or with its effects (compaction, ...). Even recently, in the legend of the world map of the status of human-induced soil degradation, Oldeman et al. (1991) included sealing and crusting

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in the same section as compaction caused by the use of heavy machinery. However, soil crusting has been increasingly regarded as a specific form of soil degradation which deserves detailed scientific investigations and publications (Cary and Evans, 1974). The first symposium devoted to soil crusting was organized in Ghent (Belgium) in 1985 (Callebaut et al., 1986) and was followed by those of Athens (U.S.) in 1991 (Sumner and Stewart, 1992) and of Brisbane (Australia) in 1994 (So et al., 1995).

The aim of this chapter is to summarize various aspects of soil crusting with a peculiar focus on the methods for assessment of this type of soil degradation. Although approaches are generally the same as those of soil science, some peculiar methods had to be developed due to the very small thickness (often < 1 mm) of most surface crusts. This chapter will primarily review the most recent studies.

II. Assessment of Soil Crusting

The main difficulty in assessing soil crusting results from its various forms of expression. Soil crusting can be monitored directly through morphological changes, or indirectly through decrease in infiltration capacity or increase in surface strength (Table 1).

A. Macro- and Micromorphological Approaches

When wetted the smallest clods are the first to slake (Johnson et al., 1979, among others) and to be gradually incorporated into a crust. Boiffin (1986) proposed a simple method to monitor this process under field conditions. It is based on the index D_{min} which designates the diameter of the smallest clods which can be easily recognized and remains unincorporated into the crust. D_{min} increases gradually with cumulative kinetic energy of rainfall and is independent of the initial aggregate size distribution. The slope coefficient of the linear regression between D_{min} and cumulative kinetic energy can be considered as an intrinsic index of susceptibility to crusting. This method seems to be best adapted to loamy soils but cannot be used for sandy soils, the structure of which tends to collapse too rapidly under rainfall (Valentin, 1988).

Many scientists since Duley (1939) found it necessary to use a microscope to study soil crusts. The recent critical review of 54 papers reporting on the examination of thin sections or scanning electron micrographs of soil crusts (Bresson and Valentin, 1994) showed that most of them (46) were issued during the last decade. While the main papers aimed at carefully characterizing crust types and forming processes, only a few authors (e.g., Chen et al., 1980; Tarchitzky et al., 1984; Luk et al., 1990; Valentin, 1991; Bresson and Cadot, 1992) sampled time-sequences to monitor the various crusting stages.

Table 1. Indices for assessment of soil crusting

Criterion	Definition	Main sources
A. Morphological		
1. Field monitoring of Dlim	Dlim = Diameter (mm) of the smallest clod not incorporated in the structural crust	Boiffin (1986)
B. Decrease in infiltration	S.I.1 = $\Delta I/\Delta T$	Poesen (1986)
1. Sealing index (S.I.1)	ΔI (mm h^{-1}): difference between steady and initial percolation rates under rainfall simulation ΔT (h): corresponding time interval	
2. Sealing index (S.I.2)	S.I.2 = Conductivity of unsealed soil/Conductivity of sealed soil	Roth (1992)
3. Sealing index (S.I.3)	S.I.3 = Conductivity of underlying layer/Conductivity of seal	Vandevaere et al. (1996)
4. Sealing susceptibility (S.S.)	S.S.: Slope of S.I. as a function of cumulative rainfall energy	Bohl and Roth (1993)
C. Increase in surface strength		
1. Strength index ($1/P_{20}^2$)	P_{20}: penetration (mm) by a standard fall-cone penetrometer at a moisture content of 20%	Luk and Cai (1990)
2. Crusting index ($\Delta\tau$)	$\Delta\tau = \tau_f - \tau_i$ Change in shear stress (fall-cone penetrometer)	Bradford and Huang (1992)

B. Indirect Measurements

In addition to morphological changes, soil crusting is associated with a dramatic reduction in the saturated hydraulic conductivity of soil surface which can be used as a sealing index (Pla, 1986). The rate at which infiltration intensity decreases under rainfall simulation at constant rainfall intensity was also proposed as a sealing index (Poesen, 1986; Table 1). This index reaches a maximal value for a mixture consisting of 90% fine sand and 10% silt. As another sealing index, Roth (1992; Table1) proposed the ratio between the saturated hydraulic conductivity of unsealed soil samples and samples that had been subjected to simulated rainfall with a given energy (e.g., 750 J m^{-2}). This index ranged from 1.03 for a tropical clay loam to 10.56 for a temperate silt loam. As for D_{min}, the sealing index can be plotted against the cumulative rainfall energy. The slope of the regression of the sealing index as a function of rainfall energy was also proposed as a measure of sealing susceptibility (Bohl and Roth, 1993). A similar index can be used for soils in situ using disc permeameters and micro-tensiometers to measure the ratio of the hydraulic conductivity of the directly underlying soil and that of the soil crust (Vandervaere et al., 1996).

Since surface strength increases when crust develops, a crusting index can be defined as the change in shear stress (Bradford and Huang, 1992) during a one-hour simulated rainstorm of about 60 mm h^{-1}, using a fall-cone penetrometer (Al-Durrah and Bradford, 1981; Bradford and Grossman, 1982). The increased strength of the surface soil can also be monitored as a result of crust development, using a soil strength index defined by Luk and Cai (1990) as $1/P_{20}^2$, with P being the penetration (in millimeters) by a stand fall-cone penetrometer at 20% moisture content estimated from penetration-soil moisture regression equations. Whatever the index, it must be stressed that because of the very little thickness of surface crust, strength measurement can often involve some combination with the soil underneath and therefore, cannot be regarded as an accurate strength of the surface crust. Arndt (1965b) developed a method for direct measurement of the impedance of soil seals, which involves mechanical probes buried prior to seal formation.

III. Prediction of Soil Crusting

A. Textural and Soil Organic Matter Indices

Monitoring changes in morphology, infiltration capacity and soil strength is often tedious and costly. Many attempts have been made therefore to directly derive the soil's susceptibility to crusting from simple and more available data like texture and organic matter content (Monnier and Stengel, 1982; Pieri, 1989; Table 2).

Table 2. Indices for prediction of soil crusting

Criterion	Definition	Main sources
A. Soil organic matter ratio		
Clay	S = Organic matter content (%) x 100/Clay (%)	Monnier and Stengel, 1982
Clay + silt	S = Organic matter content (%) x 100/[Clay (%) +Silt (%)]	Pieri, 1989
B. Dispersion test		
Emerson classification test	8 classes of soil after immersion of dry aggregates and remolding	Emerson, 1967
C. Structural stability	Percent of water stable aggregates >0.5 mm	
Percent water stable	IS = (Cl+silt) / [(Ag_{a+} Ag_{b+} Ag_c: / 3) - 0.9 C.Sand]	
aggregates	Percent wet-sieved stable aggregates after pretreatment with ethanol	Bryan, 1976
Hénin index	(Ag_a:), benzene (Ag_b) and water (Ag_c)	Hénin et al., 1958
	C = W5 - W10	
D. Atteberg limits	Water content (%) 5 and 10 blows of the Casagrande cup	
Consistency index (C_{5-10})		De Ploey and Mücher (1981)
	Resistance to rupture (Mpa) of a standardized remolded soil	
E. Strength indices	briquette	
Modulus of rupture (MOR)		Richards (1953)
	RS = (BL)g/1.209 $(m/\rho)^{2/3}$	
	BL: load at initial break, g: acceleration due to gravity, m: mass of	
Rupture stress (RS)	aggregate, ρ: aggregate density	Skidmore and Powers (1982)

B. Dispersion Tests

Many dispersion tests have been proposed to predict the susceptibility of soils to crusting from the simple water dispersible silt plus clay percentage (Painuli and Abrol, 1988) and the dispersion ratio (dispersed clay + silt/total clay + silt; Middleton, 1930) to a more sophisticated classification test (Emerson, 1967) and the ultrasonic dispersion test (Imeson and Vis, 1984).

C. Instability Indices

A wide variety of tests based on soil structural instability have been developed to predict soil susceptibility to crusting. They have been regularly reviewed (e.g., Hamblin, 1980; Srzednicki and Keller, 1984; Loch, 1989; Loch and Foley, 1994; Le Bissonnais and Le Souder, 1995; Valentin, 1995) and compared (e.g., De Vleeschauer et al., 1978; Churchman and Tate, 1986; Matkin and Smart, 1987; Valentin and Janeau, 1989; Wace and Hignett, 1991; Lebron et al., 1994). A growing number of authors consider such tests unsatisfactory (Francis and Cruse, 1983; Webb and Coughlan, 1989; Loch, 1989; Le Bissonnais, 1990; Dickson et al., 1991; Rasiah et al., 1992) mainly because the ranking of soils is greatly determined by the pre-wetting and wetting procedures, the antecedent soil moisture and the size of aggregates. However, sealing susceptibility can be more satisfactorily predicted when the size distribution of the particles and/or fragments released by aggregate breakdown is considered (Le Bissonnais, 1990; Loch, 1989; Loch and Foley, 1994; Roth and Eggert, 1994).

D. Consistency Indices

Some soil engineering properties have been tested also as predictors of susceptibility to crusting, in particular the Atterberg liquid limit. This is the soil water content at which a trapezoidal moist groove of specified shape is closed after 25 taps in a Casagrande cup. Liquid limit was considered a suitable test to evaluate potential loss of soil structure (Lebron et al., 1994) and to predict the rainfall depth necessary for runoff initiation on tilled savannah soils (Valentin and Janeau, 1989). However, De Ploey and Mücher (1981) did not find any direct relationships between liquid limit and crusting susceptibility, or 'crustability'. They observed steeper upslope parts of the liquid limit curves for stable than for unstable soils. This led these authors to define a consistency index $C_{5\text{-}10}$ as the difference in soil water content between 5 and 10 blows of the Casagrande cup (Table 2). Liquefaction and consequent crust formation occurred for loamy temperate soils with $C_{5\text{-}10}<2.5$.

E. Mechanical Strength Tests

Surface crust-forming tendencies have also been evaluated by using the technique of modulus of rupture of remolded soil specimens, as described by Richards (1953), Reeve (1965) and Rengasamy et al. (1993). Although some authors (Lemos and Lutz, 1957; Arndt, 1965a) have expressed serious doubts about the validity of the underlying theory and the applicability of this test to field conditions, it has been extensively used to predict susceptibility to crusting and its effect on seedling emergence (e.g., van der Merwe and Burger, 1969; Kemper et al., 1974; Aylmore and Sills, 1982; Morrison et al., 1985; Reganold et al., 1987; Painuli and Abrol, 1988; Gupta et al., 1992; Rengasamy and Naidu, 1995).

An energy-based index of dry soil aggregate stability was developed by Skidmore and Powers (1982) based on rupture stress (Table 2). More recently, Skidmore and Layton (1992) defined the dry-soil aggregate stability as the work required to crush an aggregate, divided by the mass of the crushed aggregate.

F. Evaluation of Indices

Prior to selecting an index to characterize the crusting process or to rank soils according to their susceptibility to crusting, two main questions must be answered: (i) what aspect of crusting will be addressed? (ii) under which conditions? It would be hazardous indeed to derive infiltration properties from a strength test (Bradford and Huang, 1992), or from an aggregate stability test (Roth, 1995). Moreover, no unique index can be used to predict surface crusting inasmuch as processes are interrelated with the antecedent moisture conditions and the rainfall patterns. Valentin and Janeau (1989) suggested, for instance, to restrict the use of aggregate instability tests based on immersion such as the index of Henin et al. (1958) to the assessment of crustability where the surface soil dries before the next shower, as is the general rule in the semi-arid Tropics and also in the temperate zone during summer where storms induce a sudden wetting of previously dried aggregates. Conversely, where moist soils are submitted to less aggressive rainfall, a consistency index, like Atterberg's liquid limit, seems better adapted (Valentin and Janeau, 1989).

Selecting a crusting index also requires the verification that the assumption of correlation between this surrogate and the relevant field property has been validated. When the objective is to predict the behavior of soil under rain, the attempts to reproduce disruptive forces of natural raindrop impacts in the laboratory, by shaking, ultrasonic disruption, remolding or simulating single water drop leave much to be desired because under field conditions, a range of drop sizes are applied to a range of aggregate sizes. Therefore, field rainfall simulation has proved an invaluable method for screening soils rapidly in order to establish the stability of soil aggregates under various conditions and the permeability of the crusts once formed (Loch, 1989; Wace and Hignett, 1991; Loch, 1994; Loch and

Foley, 1994) provided that simulated rain must have an intensity and a drop-energy distribution similar to the natural rainfall (Meyer, 1994, among many others).

Despite their numerous limitations, these tests have provided the basis for a considerable amount of research which has recognized general trends among the factors affecting soil crusting.

IV. Identification of Soil Crusts

Identifying crust types is important for diagnosing the severity of soil surface degradation. Just as soil classification helps predict soil properties, crust typology aims at relating morphology to genesis and behavior. There is some confusion with terminology, however, as pointed out by Mualem et al. (1990) and Bristow et al. (1995). Nevertheless, our present understanding of crust formation has led to suggesting a general classification of soil crusts (Valentin and Bresson, 1992).

A. Crusting Development Stages

Boiffin (1986) and Valentin (1986) showed that the dynamics of the crusting process involved two main stages: (1) sealing of the surface by a structural crust, then (2) development of a depositional crust. The change from the first to the second stage mainly depends on a decrease in infiltration rate due to the structural crust development, which induces microrunoff. From that framework, Valentin and Bresson (1992) developed a general conceptual model which included distinction between the two main types of crust. Each type, which is related to a dominant specific process, can be identified in the field using simple macro- and micromorphological diagnostic features. This typology seems to account for most of the crusts described in the literature (Bresson and Valentin, 1994). It has been shown to be a useful tool for predicting infiltrability (Boiffin and Monnier, 1986; Casenave and Valentin, 1992). Also, it provides some guidelines for selecting the most suitable management practices and control techniques because the formation processes involved in a particular type of crust are identified using simple diagnostic features (Valentin and Bresson, 1992). Major types are reviewed hereafter.

B. Structural Crusts

Slaking crusts consist of a thin (1 mm to 5 mm thick) dense layer, with a sharp boundary with the underlying layer (Figure 1a). No textural separation between coarse particles (skeleton) and fine particles (plasma) can be observed. Porosity mainly depends on the size distribution of the particles released by aggregate breakdown. Some packing porosity can remain if aggregate disruption led to

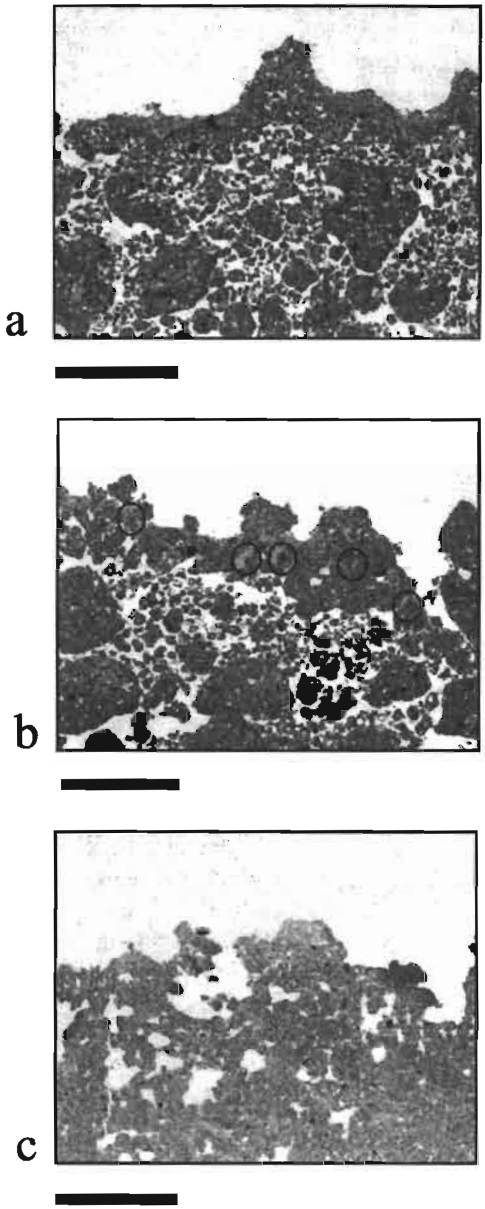

Figure 1. Structural crusts formed in a loamy soil material (repacked seedbed, Australia); (a) if the soil material was dry before rainfall, a slaking crust developed very fast; (b) if the soil material was wet before rainfall, an infilling crust developed (plain light); and (c) coalescing structural crust developed in a loamy soil on an experimental field, France (plain light).

aggregate fragments (Figure 1a). Such a disruption can be ascribed to air entrapment compression and/or to microcracking (Le Bissonnais et al., 1989). Conversely, when aggregate breakdown released basic particles, porosity is much lower. Such a disintegration (or physical dispersion) can also be due to air entrapment, but physico-chemical dispersion can play the main role in sodic soils (e.g., Agassi et al., 1981; Shainberg and Levy, 1992). The various soil and climatic conditions which control slaking have been well documented (e.g., Robinson and Page, 1950). Slaking crusts predominate when the soil is dry before rainfall (Valentin, 1981; Boiffin, 1986; Norton, 1987; Le Bissonnais et al., 1989).

Infilling crusts are mainly characterized by a clear textural separation (Figure 1b). Bare silt-sized grains form net-like infillings in the few top millimeters of the soil (Boiffin and Bresson, 1987; Le Bissonnais et al., 1989; Bresson and Cadot, 1992; Fiès and Panini, 1995). Some clay coatings can usually be observed a few millimeters deeper. Interaggregate packing voids are clogged so that porosity is reduced to the intergrain packing voids of the infilling material. Aggregates can be identified up to the soil surface. The transition with the underlying layer is abrupt. Infilling crusts develop due to raindrop impact which slowly erodes the top of surface aggregates, the resulting separated silt grains illuviating a few millimeters deeper into the interaggegate packing voids (Bresson and Cadot, 1992). This process implies that the aggregate framework remains rather stable, which explains that infilling crusts mainly develop on loamy soils when the soil is wet before rainfall.

Coalescing crusts (Figure 1c) are usually much thicker, up to 20 mm thick, and they exhibit a rather gradual transition with the underlying layers. This led Bresson and Boiffin (1990) to define a transitional microhorizon (m_{1-2}). This microhorizon differed from the underlying initial seedbed (m_1) because aggregates were more densely packed so that the soil material appeared to be continuous in 2 dimensions. Porosity remained rather high but gradually decreased towards the surface. It consisted of interaggregate packing voids which were polyconcave at the bottom and progressively developed convexities towards the surface. In the few top millimeters of the crust, porosity strongly decreased (m_2 microhorizon). The remaining voids, convexo-concave to vesicular, were less abundant, smaller and far enough from each other to infer that the 3-dimensional connexity was low. Coalescence occurs when the soil material is viscous when wet (Bresson and Boiffin, 1990; Kwaad and Mücher, 1995). The driving force is drop energy, so that coalescence must not be mistaken for slumping which occurs in hardsetting soils due to overburden pressure (Bresson and Moran, 1995).

Sieving crusts can be observed in sandy soils (Valentin, 1986; Poss et al., 1989; Greene and Ringrose-Voase, 1994; Bielders and Baveye, 1995a) where aggregates are usually nonexistent or extremely fragile. They are made up of two contrasting layers (Figure 2a). The uppermost layer, 1 to 5 mm thick, consists of loosely packed skeleton grains with the coarser grains usually concentrated at the top. Vesicles can be observed, but pore connectivity is mainly due to intergrain packing voids. The underlying layer is very thin, 100 μm to 1 mm thick. It contains a high amount of fine particles, which results in a very low porosity. The upper and lower

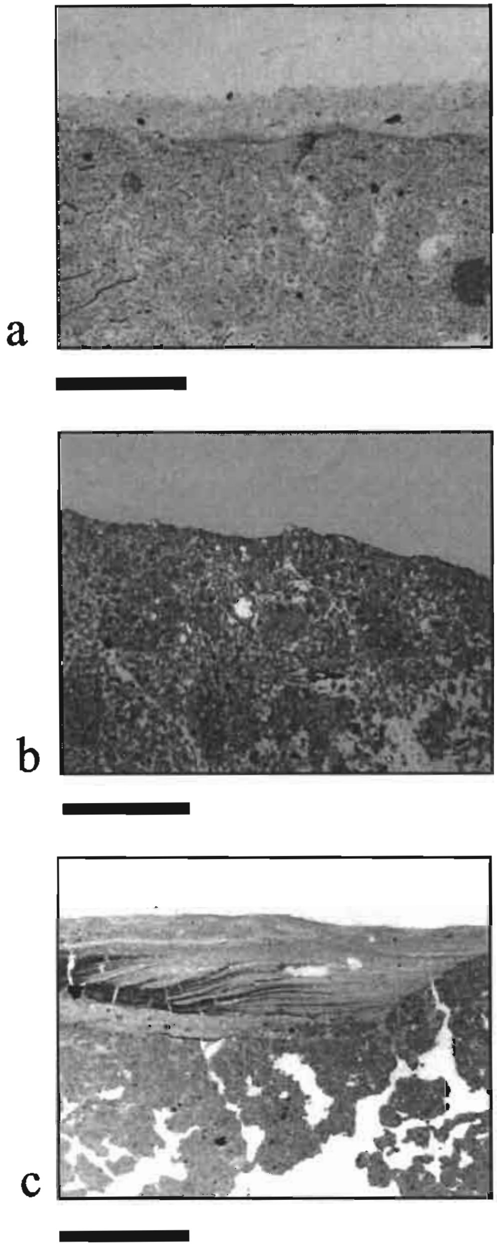

Figure 2. (a) Sieving structural crust developed in a cultivated sandy soil, France (plain light); (b) erosion crust developed in a rangeland sandy soil, Niger (plain light); and (c) depositional crust developed in a cultivated loamy soil, France (plain light).

boundaries of this plasmic layer are very sharp. As described by Valentin (1986), the impact of raindrops on sandy soils results in a winnowing process which leads to an inverse particle sorting: the finer the particles, the deeper they are concentrated. Filtration of the fine particles can enhance this initial sorting (Valentin, 1986, 1991; Bielders and Baveye, 1995b).

C. Erosion and Depositional Crusts

Erosion crusts (Figure 2b) consist of only one thin, 100 μm to 1 mm thick, plasmic layer which is very dense and coherent (Valentin, 1986). They result from the erosion of a sieving crust: when the loose coarse-textured upper layer is stripped away by the overland flow, the underlying clayey layer outcrops (Valentin, 1986, 1991).

Depositional crusts (Figure 2c) are made up of a sedimentary layer overlaying a previously developed structural crust (Boiffin and Bresson, 1987). The sedimentary layer can be very thick, 5 to 10 mm or more. Textural separation between basic particles results in alternate submillimetric microbeds more or less contrasted in texture and uncomformable with the underlying layer. Usually, the bedding is less distinct at the lower part of the sedimentary layer and the particle sorting is poorer (Bresson and Boiffin, 1990). Sometimes, aggregate fragments are mixed up with sorted basic particles. Depositional crusts develop after sealing of the surface by a structural crust. Microscale runoff concentrates the particles detached from eroded clods or ridges in interclod microdepressions or furrows. The main features of the sedimentary layer, i.e., sorting, microbedding, packing and orientation of basic particles can be related to the hydrodynamic conditions of particle sedimentation (Mücher and De Ploey, 1977; Mücher et al., 1981; Bresson and Boiffin, 1990; Valentin, 1991; Bielders et al., 1996).

D. Cryptogamic Crusts

Several authors proposed cryptogamic crusts made of algae, fungi, lichens, mosses, bacteria etc. as a typical category of surface crusts (Mücher et al., 1988; West, 1990; Chartres, 1992; Eldridge, 1993; Johansen, 1993). Most microphytic crusts, however, consist of a microbiological layer over one of the above-defined types of crust, the latter greatly controlling hydrological behavior. As emphasized by Bresson and Valentin (1994) and Chartres et al. (1994), cryptogams should not therefore be considered regardless of the type of crust they colonize (erosion crust, depositional crust etc.).

V. Conclusions and Recommendations

1. When studying soil crusting, the first major difficulty arises from the wide variety of available physical methods which have been designed: (i) to assess the impact of

surface crusts such as the decrease in infiltration capacity or the increase in surface strength and (ii) to predict soil susceptibility to crusting. In many studies, the presence of a soil crust is only betokened by one of its indirect effect, without any characterization of its properties (texture, organic matter content, chemical and mineralogical properties, thickness, porosity, etc.) and type (structural, depositional, erosion crusts, etc.). Such a common deficiency greatly reduces the possibility to predict hydraulic and strength surface behavior from crust properties and types. A better procedure would assess such characteristics, including crust morphological properties, prior to any measurement. In this respect, the use of a morphological and process-based classification system appears to be an invaluable tool.

2. As there is no unique method to assess and predict crusting, no panacea to control it can be advocated. In particular, crust management practices cannot be considered in isolation from land use and farming systems. The extreme diversity of climatic, land and human situations obviates any unique approach.

3. Due to the wide array of approaches, standardization of laboratory and field methods seems unrealistic. However, future research studies should more clearly present the experimental conditions and account for the crust types.

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