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Soil Surface Crusting and Structure Slumping in Europe

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2.3.1 INTRODUCTION

The degradation of soil surface structure by rainfall (surface crusting and structure slumping) has long been recognised to play a significant role in soil erosion. Even though runoff can be generated by low infiltration rate subsurface layers, including ploughpans or frozen subsoil (e.g. Oygarden, 2003), the degradation of soil surface structure often controls runoff triggering. This is especially true under temperate climate where gentle rainfall events (5–10 mm hr^{-1}) could not induce runoff in many soils if the soil surface were not sealed by surface crusts (the infiltration capacity of surface crusts commonly ranges from 0 to 5 mm h^{-1}; Table 2.3.1). In the same way, the role of surface crusting in runoff generation is particularly important in spring and summer when the soil is dry (e.g. Ehlers *et al*., 1980; Dijk and Kwaad, 1996), that is, when runoff is not likely to be generated by soil water logging.

Therefore, erosion risk assessment requires knowledge of the soil, climatic and management conditions that control the various processes involved in soil surface structure degradation. Suggesting relevant management practices also requires (i) diagnostic tools for determining the degradation processes involved in a particular situation and (ii) predictive tests to assess risks of soil surface structure degradation.

Soil surface structure degradation and its impact on erosion have long been studied. In addition to many textbooks, a great deal of information can be found in the proceedings of the three international working

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TABLE 2.3.1 Crust types, subtypes, diagnostic features (according to Valentin and Bresson, 1998) and infiltrability (from Valentin and Bresson, 1992; completed with data from Kwaad and Mullingen, 1991; Fiès and Panini, 1995; Bresson *et al.*, 2001)

Type	Subtype	Main process	Diagnostic features	Infiltrability (mm h^{-1})
Structural	Slaking	Aggregate disruption	Thin, dense layer, with sharp lower boundary	1–20
	Infilling	Aggregate erosion and illuviation of eroded particles	Thin, dense layer, with textural separation and rather sharp lower boundary	5–10
	Coalescing	Aggregate deformation	Thick, continuous layer, with convexo-concave voids and progressive lower boundary	2–9
	Agglomerating	Fragment agglomeration	Closely packed agglomerates	No data
	Packing	Particle compaction	Closely packed textural units	25–45
	Sieving	Particle sorting and filtration	Loose sand grains upper layer overlying a thin plasmic layer	0–15
Erosion		Erosion of sieving crusts	Thin plasmic layer at the surface	0–2
Depositional	Runoff	Sedimentation in running water	Poorly sorted micro-bedding	1–5
	Still	Sedimentation in still water	Highly sorted micro-bedding	0–2

meetings which have been held on surface crusting and structure slumping processes, consequences and management: Ghent (Callebaut *et al.*, 1986), Athens (Sumner and Stewart, 1992) and Brisbane (So *et al.*, 1995).

This chapter will deal with (i) a short overview of crusting and slumping processes, contolling factors and consequences, using mainly recent studies carried out in Europe, (ii) surface crusting occurrence in Europe, (iii) structure slumping occurrence in Europe and (iv) a few research opportunities.

2.3.2 CRUSTING AND SLUMPING PROCESSES

2.3.2.1 Definitions

Surface crusting. Two terms can be found in the literature: surface seal and surface crust. Most often, 'seal' refers to water infiltration issues and 'crust' refers to soil strength issues. Therefore, a seal which dries after rainfall becomes a crust, and a crust which rewets under the following rainfall event becomes a seal. Moreover, 'surface sealing' also refers to the consequences of growth in urbanisation and transport infrastructure. Therefore, the term soil 'crust' should rather be used, whether the soil is dry or wet.

A crust is a thin, often transient, soil-surface layer which develops under rainfall or irrigation. A crust usually results from processes induced by wetting and raindrop impact, such as aggregate disruption and/or particle (fragment) relocation and/or compaction. The decreased interaggregate and/or interparticle packing porosity leads to reduced saturated hydraulic conductivity and results in increased strength when dry.

Structure slumping. The term 'slumping' has been suggested for hardsetting soils (Mullins *et al.*, 1990) to distinguish the collapse of seedbeds on wetting from the shrinkage induced by subsequent drying [hardsetting is a soil structure degradation process in which, during drying, the surface horizon sets to a hard, structureless mass that is difficult to cultivate, impedes seedling emergence and restricts root growth (Mullins *et al.*, 1990)]. Slumping results from processes similar to those involved in crusting (Mullins *et al*., 1990), except that overburden pressure is expected to dominate slumping rather than rainfall kinetic energy (Bresson and Moran, 1995). Although slumping in hardsetting soils has usually been considered through its consequences on crop yields and tillage management, it is also expected to reduce water infiltration rate (Mullins, 1998), all the more because the decrease in macroporosity affects the whole seedbed or tilled layer and not only the top few millimetres.

2.3.2.2 Processes

Surface crusting has been extensively studied in Europe. A conceptual morphological model for soil crusting and slumping has been suggested by Le Bissonnais (1996) and Bresson and Moran (2004). This model includes three main processes: (i) aggregate disruption (abrasion, compression of entrapped air, differential swelling, physico-chemical dispersion) or aggregate deformation, (ii) particle/fragment relocation (infilling, splash, micro-mudflow, micro-deposition) and (iii) compaction (raindrop kinetic energy, capillary forces, overburden pressure).

Crusting has been shown to be a dynamic process, which includes two main development stages (Boiffin, 1986; Valentin, 1986): (i) sealing of the surface by a structural crust and then (ii) 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 formation, which induces micro-runoff.

The development rate of the structural crust, and also the hydraulic and mechanical properties of the crust, are closely related to the size of the fragments resulting from the aggregate disruption processes (e.g. Le Bissonnais, 1990; Roth and Eggert, 1994). Therefore, structural crust subtypes depend not only on the soil material properties (texture, organic matter content and aggregate stability) but also on the initial water content of the seedbed and on the rainfall characteristics (e.g. Bresson and Cadot, 1992; Le Bissonnais and Bruand, 1993; Fiès and Panini, 1995).

The crust types and the related diagnostic features suggested by Valentin and Bresson (1998) are summarized in Table 2.3.1. Microphytic crusts are not included in this typology, despite their practical significance in soil erosion (e.g. Solé-Bénet et al., 1997; Maestre *et al*., 2002). Indeed, algaes and lichen can colonise any type of crust, so that they should be considered as a particular vegetation cover rather than a particular type of crust (Bresson and Valentin, 1994).

Relationships between crust types and hydraulic properties have been established (e.g. Valentin and Bresson, 1992; Fiès and Panini, 1995), which shows that crust typology may be useful for implementing an expert-based prediction model of soil surface hydraulic behaviour (Table 2.3.1).

Structural slumping results from aggregate dispersion, disruption or deformation (Mullins *et al*., 1987). Slumping processes have been mainly studied in hardsetting soils (e.g. Mullins, 1998) because, in such soils, the structural collapse resulting from wetting greatly controls the hardening on drying (Bresson and Moran, 1995).

Hardsetting soils are common in the tropics but have seldom been described in Europe (Young, 1992). However, a particular subtype of structural crust (Table 2.3.1), called ‘coalescing’ (Bresson and Boiffin, 1990) or ‘aggregate welding’ (Kwaad and Mücher, 1994), and recently described in France and The Netherlands, respectively, was ascribed to aggregate deformation under viscous conditions, that is, a process similar to slumping. In the same way, recent attempts to model the bulk density profiles within structurally degraded seedbeds have associated a crusting component and a slumping component (Bresson *et al*., 2004). Also, agglomeration by wetting of the fine fragments that commonly result from tillage operations in dry soils may result not only in surface crusts but also in slumped surface horizons (Bresson and Moran, 1995). Similarities between crusting and slumping prompts the consideration of microstructure characterization when studying slumping. For instance, Bresson and Moran (2003, 2004) investigated the role played by compaction versus aggregate disruption on seedbed slumping. They showed that aggregate disruption on wetting did not induce much increase in bulk density but a strong decrease in macroporosity, whereas compaction by either rainfall kinetic energy or overburden pressure led to a strong increase in bulk density.

2.3.2.3 Controlling Factors

The soil, climate and management conditions are well known to control surface structure degradation hazard and rate. Soil characteristics, such as texture (e.g. Fiès and Panini, 1995), clay mineralogy (e.g. Mermut *et al.*, 1995), organic matter content (e.g. Le Bissonnais, 1996) and exchangeable sodium percentage (e.g. Robinson and Philips, 2001), and also slope steepness (e.g. Poesen, 1984) and stone cover (e.g. Poesen and Ingelmo-Sanchez, 1992), play a major role in aggregate stability and therefore in soil susceptibility to surface structure degradation. Other controlling factors depend greatly on management practices: initial conditions such as aggregate size distribution (e.g. Bresson and Moran, 1995) and water content (e.g. Le Bissonnais, 1990), and also soil surface conditions such as surface roughness (Roth and Helming, 1992) and vegetation cover (e.g. Martin, 1999). Climate also plays a great role through rainfall characteristics such as rainfall intensity and kinetic energy (e.g. Helming *et al.*, 1993).

The soil, climate and management conditions also control the type of crust that may form. For instance, on loamy temperate soils, a slaking crust will quickly form if the soil was dry before rainfall, and an infilling crust will slowly develop if the soil was wet (e.g. Bresson and Cadot, 1992). Conversely, on highly unstable silty soils, a coalescing crust usually develops whatever the initial state (e.g. Bresson *et al.*, 2001).

2.3.2.4 Consequences on Erosion

Soil surface structure degradation plays a significant role in Hortonian flow generation, because it leads to a lower infiltration rate, which increases runoff hazards, and to lower surface roughness, which decreases surface detention. Decreased surface roughness also increases flow velocity and therefore the capacity to detach and transport soil particles (e.g. Roth and Helming, 1992).

However, its effects on several erosion subprocesses are ambivalent (Poesen and Govers, 1986). Soil surface structure degradation usually leads to increased soil cohesion, which may eventually lead to lower particle detachment and sediment concentration (e.g. Kwaad and Mullingen, 1991). In cultivated catchments of the northern Paris basin, crusted fields are the main contributors of overall runoff, whereas most of the soil loss comes from freshly tilled, well-structured fields (e.g. Martin, 1999).

2.3.3 SURFACE CRUSTING IN EUROPE

Changing agriculture in the last 50 years has greatly enhanced the occurrence of erosion in cropping systems of western Europe (Monnier and Boiffin, 1986). Intensive agricultural practices and specialisation of large areas in cash crop production has led to lower soil organic matter content. In addition, the increase in acreage of spring crops which do not cover the soil surface in winter has increased the erosion hazards (Martin, 1999). This is especially true in the temperate areas of Europe, where the rainfall intensity is rather low, which means that runoff generation most often requires the infiltration rate to be reduced by surface structure degradation such as crusting and slumping (e.g. Kwaad and Mullingen, 1991).

2.3.3.1 Temperate Areas

Soil surface crusting is common in western Europe, especially on the cultivated silty soils that develop on the widespread loess deposits (Catt, 2001) and that are usually Luvisols, i.e. clay depleted in the upper horizons.

This might explain why most studies on crusting were carried out in the European loess belt: Belgium (e.g. De Ploey and Mücher, 1981; Poesen and Govers, 1986), Croatia (Racz, 1986; Kisic *et al*., 2002), Finland (Yli-Halla *et al*., 1986), France (e.g. Bresson and Boiffin, 1990; Le Bissonnais, 1990; Auzet *et al*., 1995), Germany (e.g. Ehlers *et al*., 1980; Gross and Tebrugge, 1992; Roth and Eggert, 1994), Hungary (Varallyay and Lesztak, 1990), The Netherlands (e.g. Imeson and Kwaad, 1990; Kwaad and Mücher, 1994), Sweden (Stenberg *et al*., 1995) and UK (e.g. Boardman and Hazelden, 1986). Nevertheless, crusting has also been described on other light-textured soils, namely soils developed on glacial and periglacial deposits (Yli-Halla *et al*., 1986; Vensteelant *et al*., 1997; Roth, 1995), alluvium (Gross and Tebrugge, 1992) and sandy drifts (Gross and Tebrugge, 1992). Sodic soils, which are extremely prone to soil structure degradation through physico-chemical dispersion, are much more common in central Europe than in western Europe. However, few studies dealing with surface crusting in sodic environments have been published in international journals, except in Hungary (Varallyay and Lesztak, 1990).

In many studies which deal with erosion processes, soil surface crusting is often simply cited as a cause of runoff generation, but not described and even less discussed. Usually, depositional crusts can be identified in the literature, but the various types of structural crusts can seldom be determined on the basis of the data provided. Slaking crusts seem to be common in most soils, whereas coalescing crusts (Figure 2.3.1d) are described only in the most light-textured, unstable soils (Kwaad and Mücher, 1994; Bresson and Boiffin, 1990; Bresson *et al*., 2001).

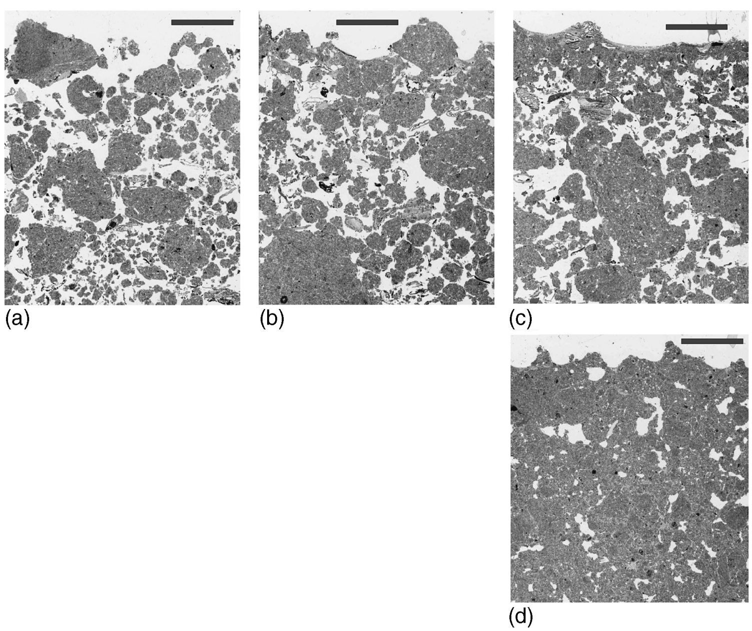

Figure 2.3.1 Surface structure degradation of a Typic Hapludalf developed on a silty loam loess deposit in the Paris basin (reconstructed seedbeds exposed to a 19 mm h^{-1} simulated rainfall). Soil amended with urban waste compost: (a) initial structure; (b) incipient structural crust (infilling) after 5 mm of rainfall; (c) incipient depositional crust developping on a structural crust after 19 mm of rainfall. Untreated soil: (d) slumped seedbed after 19 mm of rainfall. (Vertical thin sections, plain light, scale bar 10 mm)

2.3.3.2 Mediterranean Areas

In the Mediterranean areas of Europe, rainfall intensity may be high enough to trigger surface runoff whether the soil surface is degraded or not (e.g. Uson and Ramos, 2001). However, because of the higher rainfall kinetic energy, scarcer vegetation cover and lower soil organic matter content, surface structure degradation commonly occurs on most soil materials, which greatly enhances surface runoff and subsequent erosion (e.g. Ramos *et al*., 2000). For the same reasons, surface crusting also occurs in noncultivated situations (e.g. forests, rangelands and steppes). Silty and loamy soil materials, which are prone to aggregate slaking, are especially affected by crusting (e.g. Léonard and Andrieux, 1998; Ramos *et al*., 2000), but crusts also develop on a wide range of more stable materials such as clay materials: black marls (Malet *et al*., 2003) and molasse (Boudjemline *et al*., 1993; Léonard and Andrieux, 1998) in southern France, schists in Portugal (Shainberg *et al*., 1991) and Spain (Valcarcel *et al*., 2003) and alluvium in Portugal (Shainberg *et al*., 1991), Italy (Pagliai *et al*., 1995) and France (Léonard and Andrieux, 1998). Several studies in Spain (Solé-Benet *et al*., 1997; Canton *et al*., 2001) and Italy (Robinson and Philips, 2001) have dealt with badlands where crusts were shown to enhance runoff.

As opposed to temperate areas, sodic soils which are sensitive to structure degradation through physico-chemical dispersion are widespread in Mediterranean areas in Europe. However, most studies dealing with sodic soils directly relate surface runoff and erosion to the ESP or the dispersibility of the soil material, and do not attempt to characterise crust development or crust hydraulic properties (e.g. Robinson and Philips, 2001). As pointed out by Bresson and Valentin (1994), crust development in clayey and sodic environments should be related to swelling and cohesion rather than to the physico-chemical dispersability *sensu stricto*.

Only in a few papers can the crust type be identified or inferred from the data provided, with the exception of depositional crusts, which are easily recognized. In cultivated soils, e.g. soils under viticulture, slaking crusts seem to be common, but coalescing crusts have also been described in nonsodic loamy soils (Uson and Poch, 2000).

2.3.3.3 Relationships Between Crust Types and Climate

Microphytic crusts have been extensively studied in arid and semi-arid climates, especially in the USA, Australia and Africa. Such crusts have also been observed in arid and semi-arid areas of Mediterranean Europe (e.g. Solé-Benet *et al*., 1997; Maestre *et al*., 2002) and in temperate areas of Europe (Pluis and de Winder, 1989). This means that the abundance of a particular type of crust under specific environmental conditions does not necessarily imply that such a crust type cannot develop elsewhere.

Whatever the climate, sandy soils may also be affected by crusting. In these soils, a particular type of structural crust develops (‘sieving’ crust, Table 2.3.1), that has been extensively studied in semi-arid intertropical areas (e.g. Valentin, 1986; Bielders and Baveye, 1995). In temperate climates, however, only a few studies have been devoted to crusts developed on sandy soils (Valentin and Bresson, 1998; Larue, 2001). This lack of interest might be due to the low fertility potential of such soils. Sandy materials usually lead to poor, acidic soils which are covered by forest and meadows where crusting is not expected to occur. If cropped, these soils are usually affected by severe slumping and compaction processes, so that crusting might not appear to be the main structure degradation problem.

2.3.3.4 Surface Cruting Sensitivity Map of Europe

From the above review of international scientific journals and databases, it appears that surface crusting has been studied on a rather small number of sites. In order to overcome the lack of geographic information on the occurrence of this process, a map of crusting sensitivity (Figure 2.3.2), based on the Soil Geographical Data Base of Europe, has been suggested (Le Bissonnais *et al*., 2005). In this study, crusting sensitivity is

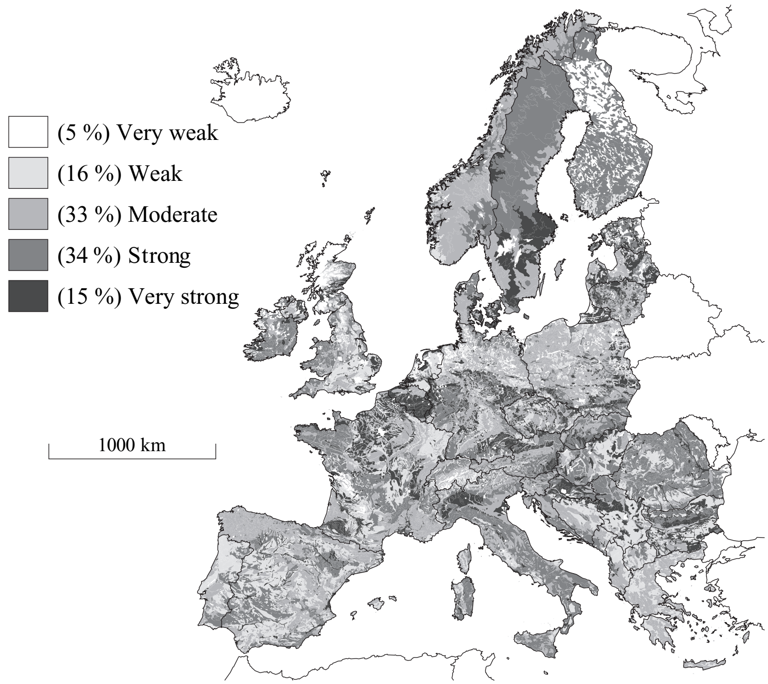

Figure 2.3.2 Soil crusting sensitivity map of Europe

characterised using two parameters. The textural parameter comes from the dominant soil surface texture (described by five classes in the database). The physico-chemical parameter is derived from the soil name at the third classification level, by taking into account the positive or negative effect of organic matter content, exchangeable sodium percentage, carbonates and other pedogenetic characteristics on structural stability. Because only few soil parameters are explicitly present in the Soil Geographical Data Base of Europe, the pedotransfer rules used in this expert-based model of crusting sensitivity are rather rough. However, they are consistent with the current knowledge of the processes involved in soil surface crusting. Therefore, this map may constitute an interesting guide for further investigations on the occurrence of soil surface crusting in Europe.

2.3.4 STRUCTURE SLUMPING IN EUROPE

Although slumping has mainly been studied in hardsetting soils, which are widespread in the tropics, it is expected to occur in unstable, sandy soils of most climatic zones, including the temperate and Mediterranean zones (Mullins *et al.*, 1990). In Europe, it has mainly been studied in the UK, on sandy loam soils with low organic matter content (Young *et al.*, 1991; Young, 1992), where slumping and compaction might not be easily delineated (Young, 1992). Only a few references can be found to other European countries: in The Netherlands (Kwaad and Mücher, 1994), Sweden (Stenberg *et al.*, 1995) and France (Figure 2.3.1d) (Bresson *et al.*, 2001).

The typology of soil surface characteristics suggested by Léonard and Andrieux (1998) includes both the surface crust and the underlying tilled layer. This means that slumping and/or compaction of the layers underlying the crust played a significant role in the surface hydraulic properties of the light-textured soils in the wine-growing Mediterranean catchment that they studied. In their study on the effect of surface roughness and structure on runoff generation, Gascuel-Odoux *et al*. (1991) also provided evidence of a compacted horizon underlying the depositional crusts. Moreover, the global slumping of seedbeds is often recognized by farmers, and such a process is commonly called in French ‘prise en masse’ (Boiffin and Sébillotte, 1976). Therefore, slumping is likely to be rather common in most light-textured soils of Europe. It is surprising that only a few papers devoted to slumping in Europe have been published in international soil science journals. Given that slumping soils are also prone to crusting under rainfall and to compaction under tillage operations and machinery traffic, the lack of publications on slumping may reflect the fact that crusting and compaction were considered as a more important issue for these soils than slumping.

2.3.5 CONCLUSIONS

In temperate areas of Europe, erosion mainly occurs on cultivated silty and loamy soils developed on loess deposits because of surface crusting, seedbed slumping or compaction of subsurface horizons. In Mediterranean areas, soil surface structure degradation is widespread and significantly increases erosion hazards. This prompted European agronomists and soil scientists to study the processes involved in order to establish relevant diagnostic tools, predictive tests, management practices and models.

In the last 10 years, i.e. since the last international working meeting on soil crusting and slumping, most studies carried out in Europe have dealt with five main issues: (i) validation of a process-based test for aggregate stability that could be used as a predictive tool (e.g. Le Bissonnais, 1996; Fox and Le Bissonnais, 1998), (ii) improvement of a comprehensive typology of crusts which could be used as a diagnostic tool (e.g. Valentin and Bresson, 1998), (iii) incorporation of soil surface characteristics (crust morphology, surface cover, surface roughness, etc.) in runoff and erosion studies (e.g. Auzet *et al*., 1995; van Wesemael *et al.*, 1996; Léonard and Andrieux, 1998), (iv) modelling crust hydraulic conductivity (e.g. Burt, 1998; Vandervaere *et al*., 1998) and (v) incorporation of crusting in soil erosion models (e.g. De Roo *et al*., 1996; Le Bissonnais *et al*., 1998; Cerdan *et al*., 2002).

Some suggestions for further studies arise from this brief overview:

1. *Crusting and slumping occurrence in Europe* To overcome the lack of geographical information on the occurrence of soil crusting and slumping in Europe, studying the national literature (journals, reports) might be helpful. Using indirect assessment techniques such as remote sensing (e.g. Mathieu *et al*., 1997; De Jong *et al*., 1999) should also significantly improve the proposed crusting sensitivity map.

2. *From conceptual crusting models to crust modelling* Combining a crust morpho-genetic typology with a process-based stability test should lead to a relevant process-based model for soil surface crust development. Whatever the model, expert-based or physically based (Le Bissonnais, 1990; Panini *et al*., 1997; Roth, 1997), more quantitative data dealing with the relationships between crust development and soil material properties, initial conditions, climatic conditions and management practices will be required.

3. *Accounting for spatial and temporal variability* Spatial variability of soil surface conditions has been shown to be very important in runoff and erosion. Surface conditions include not only the crust type and abundance but also other features such as surface roughness, soil cover (vegetation, litter, stones), surface macropores (cracks, channels) and wheel tracks (e.g. Poesen and Ingelmo-Sanchez, 1992; Auzet *et al*., 1995; Léonard and Andrieux, 1998; Cerdan *et al*., 2002; Malet *et al*., 2003). However, assessment methods still need to be improved.

Most studies on crust development have been focused on the earlier stages of seedbed structural evolution. Few studies have included the evolution of surface crusts with successive rainfalls and throughout the cropping season (Kwaad and Mullingen, 1991; Roth and Helming, 1992; Diekkrüger and Bork, 1994; Fohrer *et al*., 1999).

Eventually, this will lead to improved incorporation of crusting and slumping processes into erosion models.

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