Surface crusts of semi-arid sandy soils: types, functions and management

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Keywords: soil crusting, semi-arid region, runoff, wind erosion, water erosion

Abstract

Soil crusting is increasingly recognized as a major form of soil degradation; it impedes seedling emergence, restricts infiltration and favours rill and gully erosion. Most research on soil crusts has concentrated on the loess belts in Europe and the United States where the soils are both highly productive and very prone to crusting. In comparison, studies on sandy soil crusts remained limited, mainly because these soils are considered as marginal, especially under semi-arid conditions. The objective of this paper is to review studies on surface crusts of semi-arid sandy soils in terms of forming processes, soil-crust types, hydrological and ecological functions, and agricultural management.

Most of these studies have been based on macro- and micro-morphological approaches associated with field rainfall simulation, these methods being more appropriate than laboratory structural stability tests. The analysis of the main soil and climatic factors showed that predicting crusting can rarely be based on a unique factor but requests a combination of factors (e.g. textural properties and organic carbon content).

Soil-crusts types (structural, erosional, depositional, biological) have been related to forming processes and hydrological and erosive properties. Identifying the prevailing role of surface crusts on runoff generation in the semi-arid regions has led to hydrologic models based more on surface conditions than on soil properties. Soil crusts have ambivalent impacts on soil erosion; they protect the soil surface from wind and interrill erosion but favour rill and gully erosion. Surface crusts are inherent to semi-arid sandy ecosystems and favour the concentration of resources, which is pivotal to pastoral and agricultural activities in the semi-arid regions. Due to soil crusts, runoff and runon are important components of the water balance. It is therefore essential for water and land management of the semi-arid sandy regions to account for the spatial and temporal distribution of soil crusts.

Introduction

Although soil crusting has been mixed up for a long time with its causes (e.g. dispersion) or with its effects (e.g. surface compaction), it is increasingly recognized as a major form of soil degradation (e.g. Auzet et al., 2004). It impedes seedling emergence (e.g. Valenciano et al., 2004; Voortmana et al., 2004), restricts infiltration (e.g. Janeau et al., 2003) and favours rill and gully erosion (e.g., Valentin et al., 2005). Most research on soil crusts has concentrated on the loess belts in Europe (e.g. Bresson and Cadot, 1992) and the United States (e.g. Ruan et al., 2001) where the soils are both highly productive and prone to crusting. In comparison, studies on sandy soil crusts remained limited, because these soils are considered not only as marginal for crop production but also because most scientists have assumed that that are resistant to crusting (e.g. FAO, 1984). By contrast, these last two decades, a significant body of evidence has pointed to the high sensitivity of coarse-textured soils to surface crusting in Northern Senegal (Valentin, 1985), in Northern Niger (Valentin, 1991), in Southern Togo (Bielders et al., 1996), in Southern Niger (e.g. Rockström and Valentin, 1997; Esteves and Lapetite, 2003; Valentin et al., 2004), in Northern Burkina Faso (e.g. Karambiri et al., 2003; Ribolzi et al. 2003, 2005), in Northeastern Thailand (e.g. Hartmann et al., 2002) and in many other parts of the world as Northern China (Duan et al., 2003; Shirato et al., 2005), Zimbabwe (Burt et al., 2001) and Australia (e.g. Chartres, 1992; Isbell, 1995).

The objective of this paper is to review studies on surface crusts of semi-arid sandy soils in terms of

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factors, processes and soil-crust types, hydrological and ecological functions, and agricultural management.

Materials and methods

Because of the very thin structure of the crusts, generally less than 1 mm thick, many scientists characterized crust types based on micromorphological analysis (e.g. the review by Bresson and Valentin, 1994). A growing number of authors consider that instability tests are unsatisfactory to predict the soil sensibility to crusting (e.g. review by Valentin and Bresson, 1998). Field rainfall simulation has proved an invaluable tool to monitor crust forming processes and their impact on soil infiltrability (e. g. Valentin, 1991; Wace and Hignett, 1991; Casenave and Valentin, 1992; Bielders et al., 1996, Hartmann et al., 2002). Only few authors coupled rainfall micromorphology and rainfall simulation to monitor the various stages of crust forming in sandy soils (e.g., Valentin, 1991; Bielders and Baveye, 1995).

Crust types, processes and properties

The structural crusts are formed *in situ* while depositional crusts consist of sedimentary microlayers (Chen et al., 1980). Depending on the dominant forming process, two main types of structural crusts have been identified in sandy soils: the sieving crusts (Valentin and Bresson, 1992) and the packing crusts (Janeau et al., 2003). The sieving crusts are made of three well sorted microlayers: a top microlayer of loose coarse sand, a middle microlayer of fine sand with vesicular porosity and a lower dense microlayer of thin particles (Valentin, 1991; Bielders and Baveye, 1995). Packing crusts consist of sand grains or stable micro-aggregates tightly packed at the soil surface with very few macropores. Both types of crusts are influenced by kinetic energy of rainfall (e.g. Valentin, 1986). Sieving crusts develop on very sandy soils with very low organic matter content <1% while packing crusts develop on soils containing more organic matter and fine materials (but with silt <40%; Valentin, 2004).

They consist of a smooth, very dense, hard and thin (of the order of 0.1 mm) microlayer (Valentin and Bresson, 1992).

Structural crusts develop mainly upslope, erosion crusts mid-slope and sedimentation crusts down-slope (e. g., d’Herbès and Valentin, 1997). When these are not removed or destroyed by erosion, tillage or trampling, they tend to be colonized by cyanobacteria, algae, lichens, moses, microfungi, etc. As a result, several authors considered biological crusts as a typical category of surface crusts (e.g. Belnap and Lange, 2001; Eldridge and Leys, 2003) without considering the original physical crusts on which they develop. These underlying crusts greatly determine their hydrological behaviour (e.g., Bresson and Valentin, 1994; Malam Issa et al., 1999; Valentin, 2002) because abiotic (or ‘physical’) soil crusts differ not only in their main morphological characters (Table 1) but also in infiltrability (Table 2). Hence the interest of hydrologists for this classification to predict

Table 1. Main characteristics and properties of soil crusts in sandy soils
Sources: Casenave et Valentin, 1992; Valentin et Bresson, 1992, 2002; Janeau et al., 2003;Valentin, 2004)

Crust type	Thickness (mm)	Other characteristics	Forming process	Main factors	Mean infiltrability (mm h^{-1})#
Structural					
Packing	1-3	Tightly packed sands or stable micro-aggregates	Compaction under rainfall impact	Silt <40%, Soil organic matter >1% Heavy storms	32 (10-54) n = 14
Sieving	1-3	Vertical textural sorting with coarse particles at the top and thin particles at the bottom. Vesicular porosity	Particle sieving under rainfall impact. Air trapping (hence vesicles)	Very sandy soils, Soil organic matter >1% Heavy storms	10 (0-20) n = 31
Erosion	<1	Smooth, very dense and hard microlayer made of thin particles	Smoothening and erosion of structural crusts	Pre-existing structural crusts Runoff or/and wind.	3 (0-10) n = 20
Depositional	2->50	Vertical textural sorting with thin particles at the top and coarse particles at the bottom. Vesicular porosity	Sedimentation is still water	Pre-existing structural crusts Accumulation of water	2 (0-4) n = 9

(Range of values), n = number of samples

infiltration and runoff in the semi-arid regions from field observations and thus improve models (e.g., Casenave and Valentin, 1992; Tauer et Humborg, 1993; Bromley et al., 1997; Peugeot et al., 1997; Estevesi and Lapetite, 2003; Ndiaye et al., 2005). Because soil crusting can be identified by significant reflectance changes on the soil’s surface, soil crust-related properties such as water infiltration can be remotely sensed and mapped in semi-arid regions (e.g. d’Herbès and Valentin, 1997; Goldshleger et al., 2004).

Soil crusts have ambivalent impacts on soil erosion; they protect the soil surface from wind and interrill erosion but favour rill and gully erosion. Loose sands of the sieving structural crusts are more easily removed by wind (e.g. Goossens, 2004; Hupy, 2004), and water than the more resistant erosion crusts (e.g. Valentin, 1994). The superimposition of a biotic crust tend to make the underlying crust more resistant to erosion (e.g., Malam Issa et al., 2001; Eldridge and Leys, 2003; Valentin et al., 2004; Neff et al., 2005). Runoff produced by soil crusts tends to concentrate and form gullies even in sandy soils (e.g., Peugeot et al., 1997; Leduc et al., 2001; Descloitres et al., 2003; Esteves and Lapetite, 2003). Sandy soils are therefore generally eroded not only by sheet but also by gully erosion, even for very gentle slope gradients (Valentin et al., 2005).

Implications for land and water management

In the semi-arid zones, farmers need to weed several times during the cropping season not only to remove weed covers (e.g., de Rouw and Rajot, 2004) and limit thus competition for nutrients and water resources, but also, and often primarily to destroy the surface crust and increase water intake into the soils (Valentin et al. 2004). However, surface crusts quickly re-establish as a result of the cumulative kinetic energy of the following rainfalls. Table 2 indicates that this critical cumulative rainfall necessary for the crust to form again after tillage tends to increase with mean annual rainfall. Although a part of rainfall is lost through runoff during crust formation, and despite its short-lived positive effect, tillage is therefore essential to increase the amount of water available for crops in semi-arid sandy soils (e.g. Graef and Stahr, 2000). Tillage explains why infiltration is greater in cropped soils than in pasture soils (e.g., Casenave and Valentin, 1992; Burt et al., 2001; de Rouw, 2005).

Because crusts in sandy soils result mainly from the direct impact of raindrops, mulching of crop residues or branches is generally recommended. Since available residues are primarily used for other purposes as livestock feed or roof thatching, mulch is generally restricted to patches covered with erosion crusts. In addition to the effect of sand and seeds accumulation, mulch attracts termites that perforate pre-existing crusts and increases infiltration by a mean factor 2-3 (e.g., Casenave and Valentin, 1992; Mando et al., 1996; Léonard and Rajot, 2001). Manure application and livestock corralling on the most severely crusted patches are also valuable alternatives to restore soil surface properties (e.g. Graef and Stahr, 2000; de Rouw and Rajot, 2004; Schlecht and Buerkert, 2004; de Rouw, 2005).

The proportion of fine particles in the top layer decreases during cultivation (e.g. Ambouta and al., 1996) and increases once the land is returned to fallow (e.g., Ambouta, 1994; Abubakar, 1996). This enrichment in fine particles is primarily due to atmospheric dust deposition (e.g. Orange and Gac, 1990; Valentin et al., 2004). These textural variations influences greatly crusting processes because no erosion crust could develop when clay + silt contents falls below 5% (Ambouta, 1994), which is often the case for cropped sandy soil. By contrast, in the fallow soils, clay + silt content can approach the optimal content of 10% (e.g., Poesen, 1986; Casenave and Valentin, 1989). In the desert regions of China, straw of wheat, rice, reeds, and other plants is half buried and the other half is exposed to fix dunes. This decreases the intensity of sand flux by as much as 99.5%. Where the sand is fixed, fine particles are accumulated and a hard soil crust is formed on the dune surface, improving the stability of the dune surface (Qiu et al., 2004). Once formed, the crusts, which are neither tilled not subjected to trampling, are gradually colonised and

Table 2. Mean annual rainfall (MAR, mm) and critical cumulative rainfall necessary to form a new crust after tillage (CCR, mm) in sandy soils of the arid and semi-arid zones of West Africa

Location	Soil texture	MAR (mm)	CCR (mm)	CCR/MAR (%)	Source
Agadez, Northern Niger	Sandy	150	25	17	Valentin, 1991
Banizoumbou, Southwester Niger	Sandy	560	150	27	Röckstrom and Valentin, 1997
Bidi, Northern Burkina Faso	Sandy	620	200	32	Lamachére, 1991
Thysse Khaymor, Central Senegal	Sandy loam	660	160	24	Ndiaye et al., 2005

consolidated mosses and y green algae (e.g., Li et al., 2002) and protected from further water and wind erosion (Malam Issa et al., 2001; Valentin et al., 2004). As a result, Peugeot et al. (1997) observed in South-western Niger a much higher mean runoff coefficient (MRC) from a fallow (MRC = 23%) than from an adjacent the millet field (MRC = 5%). Most of the runoff concentrates into gullies. Since the bottom of these gullies are highly permeable (Peugeot et al., 1997; Esteves and Lapetite, 2003) a large proportion of the runoff in these gullies contribute to the water table recharge (Leduc et al., 2001).

In Northern Senegal, most severe crusting was observed in sandy exclosures where the vegetation but also soil crusts were protected from tillage and trampling (e. g. Valentin, 1985). This process has also been observed during a long-term fencing experiment in a sandy desert of Turkmenistan where crusts extended while bush and herbaceous biomass decreased (Orlovsky et al., 2004). These authors concluded that in this environment, undergrazing, as well as overgrazing, should be considered as a desertification factor. A biological soil crust with high contents of soil organic carbon and fine particles (clay + silt) was also formed within 3 years on sand dunes in an exclosure in a semi-arid, sandy grassland located in Northern China (Shirato et al., 2005).

In semi-arid areas, using mean landscape characteristics leads to a considerable underestimation of infiltration-excess surface runoff (e.g. Güntner and Bronstert, 2004). Re-infiltration and lateral redistribution of surface runoff between adjacent landscape patches need therefore to be accounted of. For instance, the mosaic of runoff generating fallows or pastures and runon-fields can be part of an efficient water-harvesting system (Rockström and de Rouw, 1997; Rockström and Valentin, 1997; Rockström et al., 1999).

Although surface crusts can hamper seedling emergence, they have overall positive effects on plant production in semi-arid sandy soils. Where rainfall input is insufficient for a continuous plant cover, vegetation benefits from the concentration of water. Such concentration is made possible only because crusts generate runoff. Crusts, especially erosion crusts, are thus inherent to the semi-arid ecosystems where they regulate scarce resources (e.g., Valentin and d’Herbès, 1999).

Conclusions

(1) Crusts form on sandy soils with silt + clay content exceeding 5%. Most severe crusting is observed for a silt + clay content of 10%.

(2) Crusts develop on sandy soils where they hamper seedling resistance and often generate runoff despite the pervious nature of the underlying soil.

(3) Accounting soil crust types improve predicting hydrological models.

(4) Crusts and associated concentrated runoff explain gully erosion of sandy soils even on gentle slopes.

(5) In the semi-arid and sandy regions, crusts must not be regarded as detrimental for the ecosystems but rather as an essential component to concentrate the poor water resources.

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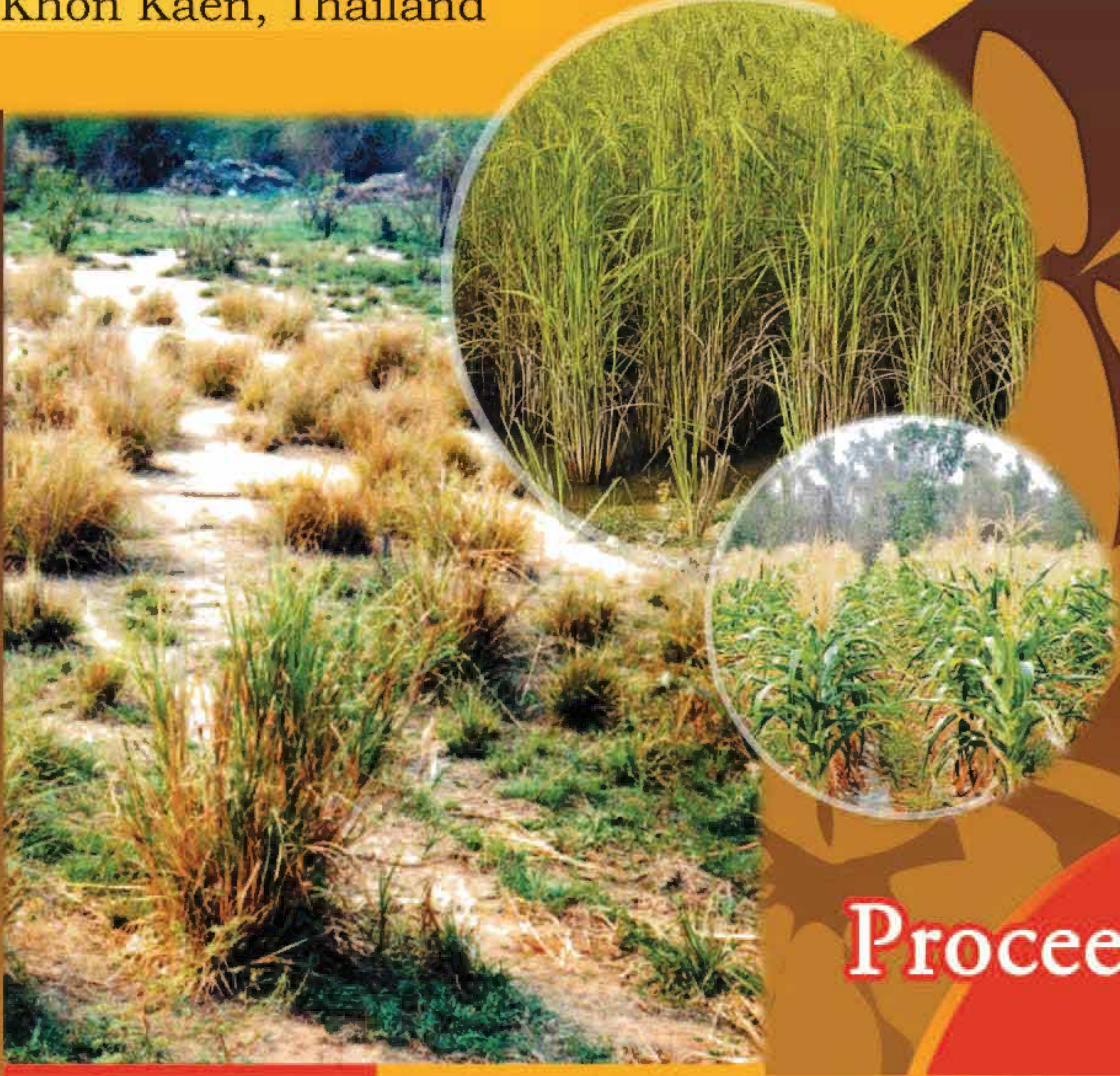

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