

The effect of soil crust ageing, through wetting and drying, on some surface structural properties

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Abstract

The crusting of topsoil, through a variety of physical and physico-chemical mechanisms, results in significant changes to surface structural and hydraulic properties. Although it is widely accepted that 'structural' and 'depositional' crusts are the two main types of soil crust, comparatively few studies have addressed the evolution of these features through a period of ageing, or weathering. Here, both structural and depositional crusts were produced on a silty soil and a clayey soil using simulated rainfall. Then, following a period of drying, the crusts were subjected to a second simulated rainfall event and a second drying period. Samples of both types of crust from both soil types were subjected to mercury intrusion analysis after both the first and second drying periods. A particle size analysis was also conducted on each of these crusts after both rainfall events. The crusts of two soil types were found to be affected to different extents by the imposed weathering procedure. The silty soil, regarded as the more susceptible to crusting and erosion, quickly yielded structural and thick depositional crusts that did not change markedly with a subsequent wetting and drying cycle. In contrast, the more structurally-stable clayey soil yielded thinner crusts, which were found to undergo more pronounced re-organisation after a second wetting and drying cycle. Both the aggregation of solids and the pore networks of these crusts were altered. These results indicate that crust ageing, through the action of periodic wetting and drying, may be a more important process in relatively structurally stable soils than in readily slaking or dispersing soils.

Key Words

crust, structure, mercury porosimetry, ageing

Introduction

Crusting of topsoil may occur during rainfall events due to the breakdown of aggregated particles at the soil surface and the redistribution of the resultant finer particles to form a closely-packed layer containing little porosity (Bresson and Valentin 1994). The mechanisms of aggregate breakdown have been shown to be multiple and varied, including the imparting of kinetic energy by raindrops, slaking due to air compression and physico-chemical swelling and dispersion. Primary particles and small aggregates are both redistributed and involved in crust formation (Bresson and Valentin 1994). There is also an extensive body of literature describing the types of crust that may form on topsoils of different textures and as a result of different rainfall conditions (e.g. Chen 1980; Valentin and Bresson 1992; Chiang *et al.* 1994). Such research has indicated that two main groups of crusts may form following rainfall; (i) 'structural' crusts, which develop by the vertical sorting of soil particles that have been disaggregated, and (ii) 'depositional' (or sedimentary) crusts, which develop by the lateral movement and settling of fine-grained particles that have previously been disaggregated (Valentin and Bresson 1992). Structural crusts are generally very thin (1-3 mm thick) with slightly variable porosity, while depositional crusts can be up to 50 mm thick and usually exhibit microbedded layers and very little porosity (Valentin and Bresson 1992).

Regardless of the mode of formation, both structural and depositional crusts cause substantial changes to soil surface physical properties, including increased bulk density (Roth 1997), the diminution of hydraulic conductivity and infiltration rate (e.g. MacIntyre 1958; Chiang *et al.* 1993) and a subsequently greater susceptibility to runoff (Le Bissonnais and Bruand 1993). Such alterations provide less satisfactory conditions for seedling emergence and increase the possibility of subsequent water erosion. However, while the mechanisms, features and subsequent effects of crust production have been well documented, the development of soil crust properties through ongoing wetting and drying cycles, or other ageing processes, has been less thoroughly addressed. For many cropping systems, the physical properties of soil crusts that develop soon after planting may change according to the various stresses that are subsequently applied to those crusts. The importance of soil crusts as a limitation to crop production may therefore vary

with time. The objectives of this work were to create structural and depositional crusts on two texturally-different agricultural soils, and to observe the impact of ageing on some structural properties of these crusts through the imposition of a further simulated rainfall and drying cycle following crust evolution.

Materials and methods

Soil

Two agricultural topsoils were used in this study. One is a silt loam from Normandy, France, and the other is a silty clay loam from the Beauce region in central France. The soil from Normandy has formed in loess and is regarded as susceptible to crusting and highly erodible. The soil from the Beauce region has formed from cryoclastic limestone, does not crust readily and is regarded as difficult to erode. Soil was taken from the top 0.15 m of agricultural fields at both locations, allowed to air-dry, and sieved to remove any gravel larger than 20 mm diameter.

Treatments and analytical methods

Soil was packed into large, plastic boxes (0.50 m × 0.35 m × 0.28 m high) to achieve a density of approximately 1.2 Mg m⁻³. The soil surface of each packed box was sculpted to include two surface “furrows” and three surface “ridges”; each of these features was approximately 100 mm in width, and all were aligned perpendicular to the long axis of each box. The base of each furrow was approximately 100 mm below the flattened top of each ridge, so as to approximate a seedbed of fine tilth for a row crop. Four boxes were packed in this manner for each soil type.

After packing, two boxes were subjected to one simulated rainfall event and the other two boxes were subjected to two simulated rainfall events. For those boxes subjected to two rainfall events, a drying period of at least 30 days separated these events. The role of the first rainfall event was to create structural crusts on soil ridges and to assist in the manufacture of depositional crusts in the soil furrows. Structural crusts approximately 1 mm thick evolved in both soil types during 140 minutes of rainfall at an intensity of 30 mm h⁻¹. To complete the production of depositional crusts in the furrows, a sediment supply protocol was developed. The soil ridges were covered from further raindrop impact, and sediment-supply trays were suspended approximately 10 cm above each furrow. The sediment-supply trays were filled with the same soil as the underlying box, wetted during the preceding rainfall, positioned on a slope of approximately 5°, and then immediately subjected to a further 40 minutes of rainfall at an intensity of 30 mm h⁻¹. Sediment produced under this rainfall was allowed to run from the supply trays into the underlying furrow to form a depositional crust approximately 5-10 mm thick. The role of the second rainfall event, at least 30 days after the first, was to effect ageing and a wetting/drying cycle on the crusts formed during the first rainfall event. This second rainfall event entailed 120 minutes of simulated rainfall at an intensity of 30 mm h⁻¹. Runoff from furrows was allowed to occur during this rainfall event via outlet holes drilled into the box at the level of the depositional crust surface. During both the first and second rainfall events, the median size of raindrops, measured with an optical spectrop pluviometer, was approximately 1.4 mm, while the kinetic energy of the rainfall was calculated to be 13 J mm⁻¹.

Following the completion of the different rainfall and drying regimes, sub-samples of structural crust, depositional crust and soil beneath the crusts (5-10 g of 3-5 mm diameter pieces) were carefully removed by scalpel from the ridges and furrows of each soil box for particle size analysis. Each sub-sample was immersed in deionised water for 10 mins (Le Bissonnais 1996) and then gently sieved by hand through a 500 µm sieve using ethanol. The particle size distribution (PSD) of the material <500 µm diameter from each treated subsample was then characterised using a laser diffraction sizer (Mastersizer S, Malvern Instruments Ltd), which quantified the proportions of 61 size fractions between 0.05 and 500 µm nominal spherical diameters. The particle size distributions of the untreated topsoils were determined using the same sieving and laser-sizing techniques on fully dispersed samples.

Additional small pieces of crust were gently extracted from both ridges and furrows of each soil box, oven-dried and subjected to mercury (Hg) injection using a Micromeritics Pore Sizer 9310. Aggregates of a similar size from just beneath the ridge crust were also sampled from each box and subjected to the same treatment. As described by Fiès (1992), this technique involves the introduction of mercury into a sample chamber with step-wise increases of pressure. As each pressure step can be related to an equivalent pore diameter using the Jurin-Laplace law, the amount of mercury intruding at each pressure

step indicates the extent to which neck-pores of that size access the sample's porosity. The 45 pressure steps used in this procedure equated to pore diameters ranging from 300 μm to 0.006 μm . Duplicate samples were analysed for each crust and soil.

Results

The two soil types examined demonstrated distinctly different crusting behaviours during the course of the simulated rainfall events and the subsequent drying periods. The formation of a structural crust commenced rapidly on the ridges of the Normandy soil boxes (<10 mins of rainfall), with complete ponding in the furrows evident after only 20 minutes of rainfall and the building of a depositional crust commencing soon after. In contrast, the Beauce topsoil furrows exhibited only minor ponding after 60 minutes of rainfall, required the full 140 minutes of rainfall to show signs of structural crust development on the ridges, and did not develop pronounced depositional crusts until sediment trays were employed. During the drying phases, the more clayey Beauce topsoil tended to crack more prodigiously across both the ridges and furrows than the Normandy soil; in the latter case, cracks were largely confined to the ridge/furrow boundary and did not generally cross those features.

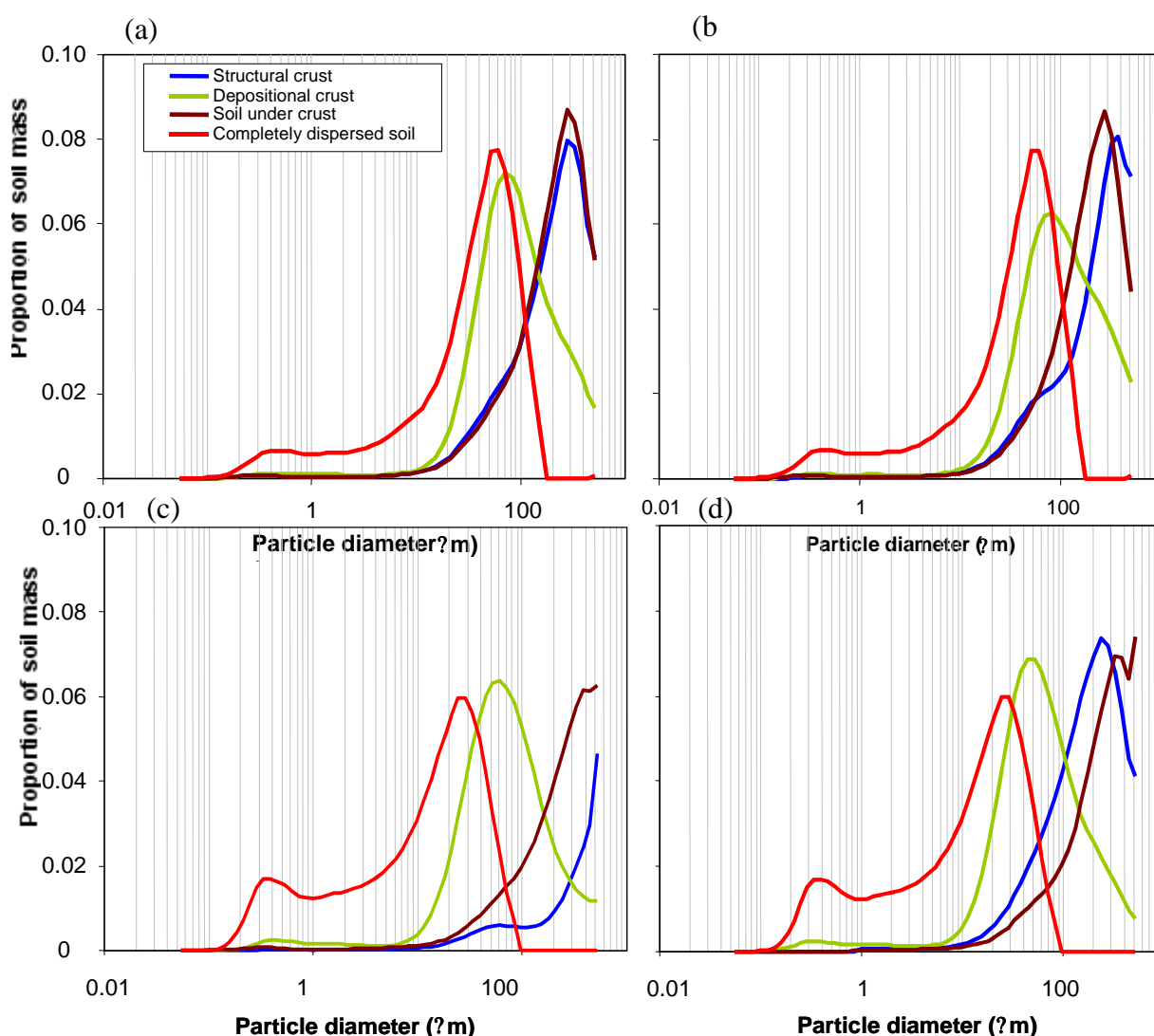


Figure 1. Particle size distributions of Normandy and Beauce topsoil and crust samples, after one simulated rainfall event (a and c, respectively) and after two simulated rainfall events separated by a period of drying (b and d, respectively).

This disparity in crusting behaviour between the two soils was mirrored by distinct differences in the granulometric properties of the crusts that formed. As indicated by Figure 1(a), the depositional crust that formed in the furrows of the Normandy soil during the first simulated rainfall event had a very similar PSD to that soil in a fully dispersed condition. The PSD of the depositional crust that formed on the Beauce soil during the first rainfall event (Figure 1(c)) was contrasted by the PSD of the fully dispersed

Beauce soil, indicating that aggregated particles were comprising the bulk of that crust. The modal diameters of the main dispersed soil particle population and the main depositional crust particle population for the Normandy soil were 55 and 70 μm , respectively, whereas for the Beauce soil the main modal diameters of the dispersed soil and of the depositional crust were 25 and 60 μm , respectively. A common feature of both soils was that the thin structural crusts that formed on the ridges after the first rainfall event exhibited PSDs that were similar to the uncrusted soils immediately beneath them; in fact, the structural crust of the Beauce soil after the first rainfall event was slightly better aggregated than the underlying soil. Following a period of drying and a second simulated rainfall event, however, the PSDs of the crusts on the Normandy soil were largely unchanged, whereas the PSDs of the Beauce topsoil crusts had shifted distinctly towards the dispersed soil PSD (Figure 1(c) and 1(d)), indicating a substantial decrease in the aggregation of those crusts.

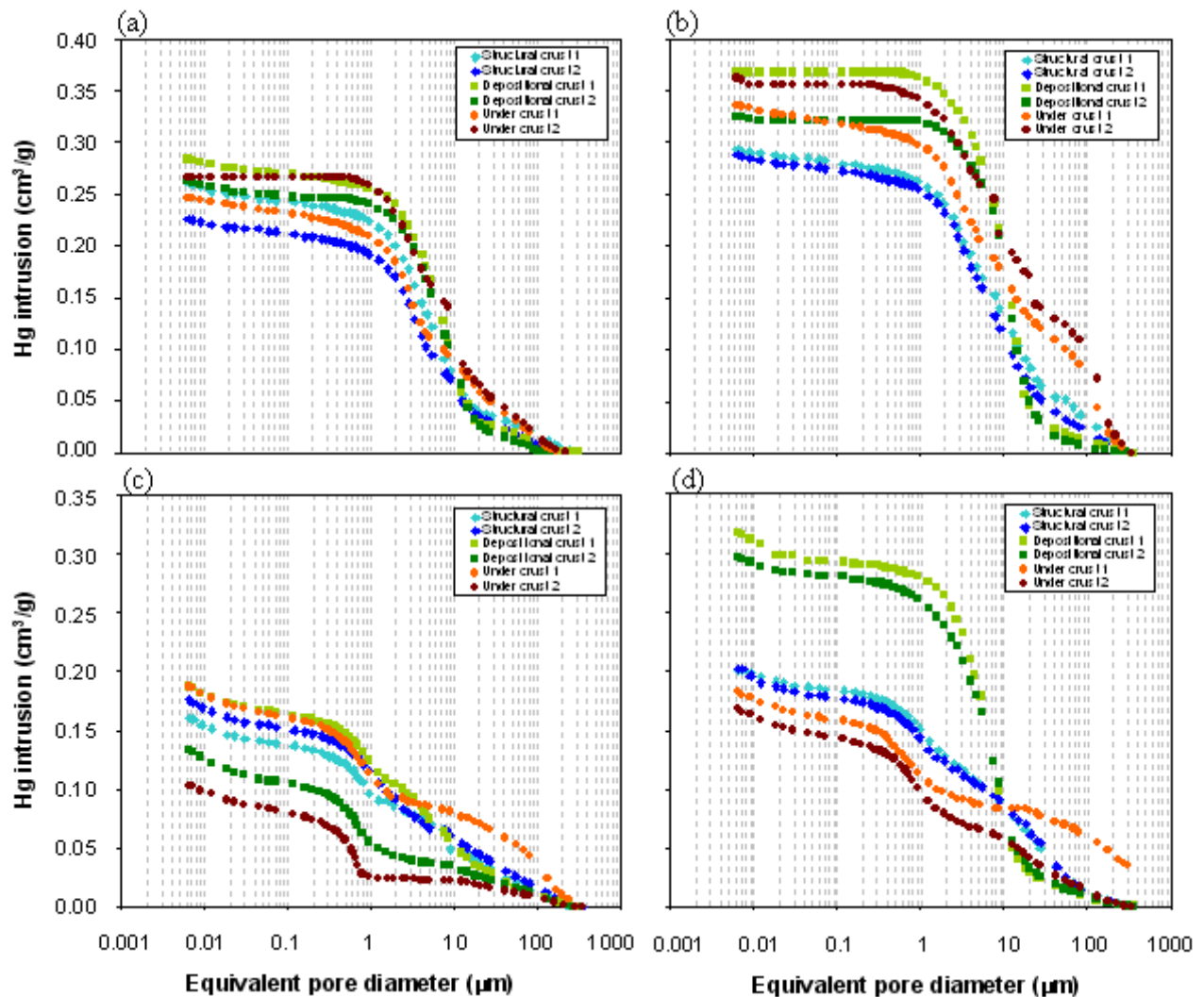


Figure 2. Mercury intrusion into samples of Normandy soil after (a) one simulated rainfall event, and (b) two simulated rainfall events, and into samples Beauce soil after (c) one simulated rainfall event, and (d) two simulated rainfall events.

The pore-network attributes of the crusts were also found to vary as a function of both the soil type and the number of wetting and drying cycles. As shown in Figure 2, both the specific volume of intruded Hg and the pore diameters at which maximum Hg intrusion took place differed between samples. After both the first and second simulated rainfall events, the Normandy soil- and crust-samples were intruded by greater volumes of Hg than the corresponding Beauce samples, indicating a greater total porosity in the former. For both the Normandy and Beauce samples, however, the depositional crusts after two rainfall events displayed distinctly greater total Hg intrusion than the depositional crusts after the first rainfall event, indicating an increase in depositional crust porosity following the second rainfall event. The structural crusts and under-crust samples from both soil types also increased in total Hg intrusion following the second rainfall event, but these changes were not as pronounced as the changes to the depositional crusts.

The Beauce soil and crusts tended to exhibit a much wider range of pore neck sizes than the Normandy samples, as indicated by flatter intrusion curve gradients. The only exceptions to this trend were the Hg-intrusion curves for the Beauce depositional crusts after two rainfall events, which exhibited a very narrow range of pore-neck sizes between 2 and 10 μm (Figure 2(d)). This same range of neck sizes was featured in the Normandy depositional crusts after two rainfall events. The main range of neck sizes for the other Normandy crust and soil samples was 0.7 to 30 μm (Figure 2(a) and 2(c)), while for the majority of the Beauce crust- and soil-samples the main range of neck sizes was 0.3 to 100 μm (Figure 2(b) and 2(d)). At the greatest mercury intrusion pressures (equivalent pore diameters $< 0.05 \mu\text{m}$), the Beauce samples consistently yielded small increases in total Hg volume intruded, whereas the Normandy samples yielded only very small or no increases in the volume of intruded Hg. This result reflects the more clayey texture of the Beauce soil, as pores less than 0.05 μm diameter have been shown to result from the packing arrangement of clay-sized particles (Fiès 1992; Bruand *et al.* 2004). The Hg intrusion curves of the structural crusts of both soils tended to mimic those of the underlying soil, reflecting the difficulty of isolating the very thin structural crusts for analysis.

Discussion

The combination of PSD and Hg intrusion data indicate that both the pore and solid phases of newly-formed Beauce crusts were affected by subsequent ageing and rainfall, whereas only the Normandy depositional crusts were somewhat altered by subsequent ageing and rainfall. This contrast in the response of the crusts of the two soils to subsequent drying and wetting can be related to the relative structural stabilities of the soils; the Normandy soil is known to be susceptible to structural breakdown on wetting and yielded fine-grained crusts very readily, while the Beauce soil is regarded as a very stable soil and developed crusts composed of more aggregated material only after a substantially longer period of simulated rainfall. The consequence of a second rainfall event was that further disruption and disaggregation of the crusts was more likely in the better-aggregated Beauce samples. The initial Normandy depositional crusts exhibited very similar PSDs to fully dispersed Normandy soil, and so the potential for further disaggregation by subsequent rainfall was not as great.

The particular feature of both the Normandy and Beauce depositional crusts that was altered by a second rainfall event was the total porosity. Intrusion of Hg increased by around a third for the depositional crusts of both soils after the second rainfall event. Intrusion amounts for the structural crusts and under crust samples also increased after two rainfall events, but not to the same extent as for the depositional crusts. The bulk of the increased porosity after the second rainfall event was accessed by a very narrow range of pore neck sizes (2-10 μm) in the depositional crusts, and a more broad range of pore neck sizes in the structural crusts. These results suggest that the action of drying and a second rainfall event, with its concomitant raindrop impact and supply of further sediment to the depositional crust, has created a more porous “cover crust” on top of the initial depositional crust. Presumably, the addition of this cover crust represents a gross example of the “microbedding” described in depositional crusts by Valentin and Bresson (1992). Sections of the cover crust were observed to readily dissociate from the underlying depositional crust when sampling was being carried out after the second rainfall and drying cycle. It is unclear, from the experiments performed here, what the effect of the second rainfall event was on the surface of the original depositional crust. Nevertheless, a model for this type of depositional crust evolution, resulting in increased crust porosity but a more narrow range of pore neck sizes, is proposed in Figure 3.

Although the total porosity changed somewhat, the pore neck sizes of the thin structural crusts that developed on both soil types were largely unchanged by a period of drying and a second rainfall event. Presumably, this reflects localised disaggregation and re-positioning of some structural crust particles under the influence of raindrop impact, but not enough to leave a very well-sorted solid phase with an associated well-sorted porosity. In particular, the Beauce structural crust, after two rainfall events, retained the same wide range of access pore sizes as the structural crust after one rainfall (0.3-100 μm), but with a slightly increased total porosity.

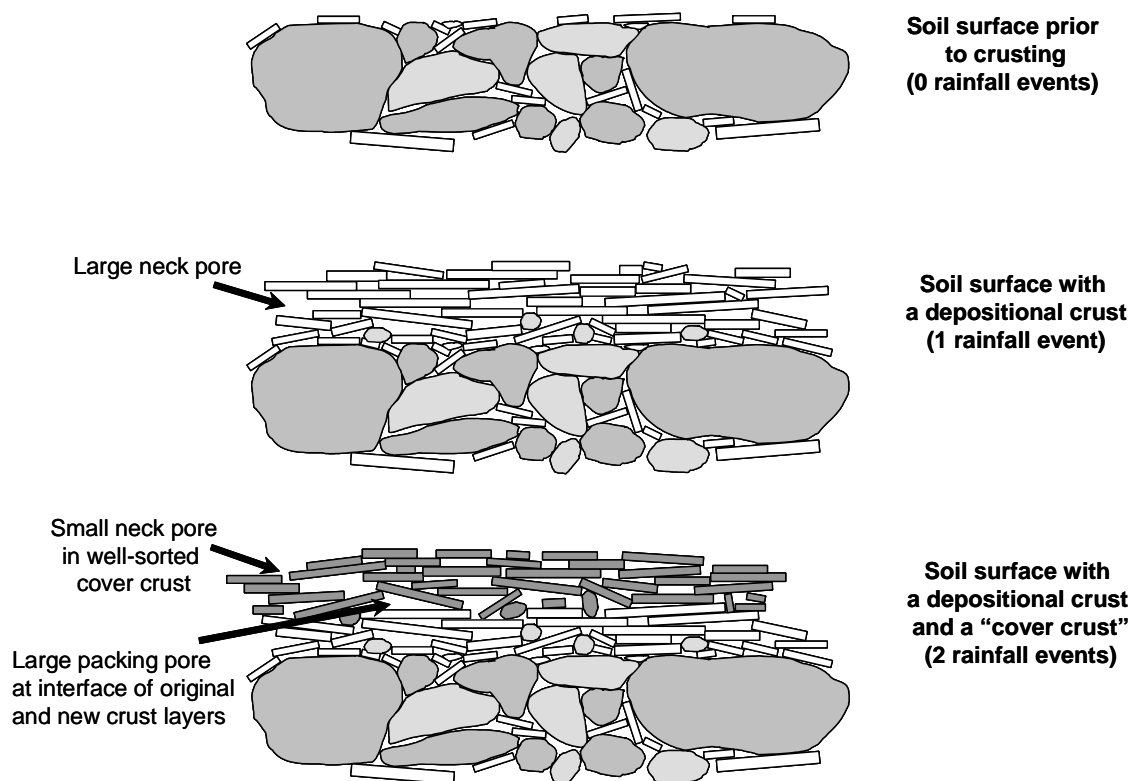


Figure 3. A schematic model of the development of a cover crust over a depositional crust in a soil type with a mixture of sand, silt and clay-sized particles.

The main soil management implication to emerge from this work is that the physical character of crusts, and therefore their impact on soil hydraulic and strength properties, may change over time with the imposition of different stresses. Of the two soil types investigated here, the better-aggregated Beauce soil is more likely to yield crusts that may undergo alteration upon weathering and repeated wetting. Although the total porosity of these crusts increased, the very narrow range of small pore sizes of the altered crusts suggests that the hydraulic properties of this material would be less favourable for seedling germination and emergence. In contrast, the more unstable Normandy soil rapidly develops both structural and depositional crusts under rainfall, but these do not appear to change greatly upon subsequent wetting and drying. So while the physical properties of the initial crusts will not be advantageous to seedlings, the ageing and re-wetting of these crusts will not cause hydraulic attributes to deteriorate further.

Conclusion

The two soil types investigated in this work, a silty loam from Normandy, and a silty clay loam from the Beauce region of central France, were both found to yield structural and depositional crusts under simulated rainfall and sediment supply. The ease of crust production differed, however, with the structurally-unstable Normandy soil developing thicker crusts more rapidly than the stable Beauce soil. Once formed, the crusts also differed in their pore and solid attributes. The Beauce crusts were comprised of more aggregated material and incorporated a range of pore sizes, but the Normandy crusts contained greater total porosity. Following a period of drying and a second simulated rainfall event, the depositional crusts of both soil types became more porous, but with a very limited range of pore neck sizes, suggesting that the re-formed crust surfaces were very well sorted. The structural crusts and below-crust soil of both soil types were not affected as much by the second rainfall event, but did show some small increases in porosity. These results suggest that a “cover crust” is produced over the original depositional crust during the second rainfall event; in the case of the Beauce soil, this cover crust represents quite a change to the properties of the original depositional crust. The ageing of crusts through subsequent drying and wetting events would therefore appear to have a greater potential for affecting the initially stable Beauce soil than the structurally unstable Normandy soil.

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