2

Soil Surface Crusting of Soil and Water Harvesting

2.1. Surface conditions and surface crusts

Soil surface conditions, essential elements of the critical zone, include vegetation cover and soil surface [CAS 89]. On large scales, they are characterized by remote sensing [DHE 97]. In the field, the main vegetation parameters generally taken into account are those that have an impact on runoff and soil erosion (Chapters 3 and 4): percentage of cover, throughfall height, density and number of layers. The same is true for those on the *stricto sensu* ground surface: litter, soil fauna constructions and pores (worms, ants, termites, etc. [JOU 08, JOU 12]), random roughness and tillage-induced roughness, the presence of aggregates and coarse fragments that are free or embedded in a crust (Figure 2.1), crust types. Most of these variables are expressed as percentages.

Physical soil crusts are characterized by very low macroporosity. They "seal" the surface of the soil, hence the term *seal*, which is used to designate crusts in their wet state. Because of their hardness when dry, they tend to protect soils from *in situ* water erosion. However, as they encourage runoff, they increase the risk of downstream erosion in rills or gullies (see Chapter 3). Several types of physical crusts can be distinguished (Figure 2.1 and section 2.2, [VAL 92a]), including structural crusts for which particle translocations are limited to a few centimeters and where the

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original aggregate-induced roughness can still be recognized, smooth and often very hard erosion crusts, and gravel crusts that embed coarse elements.

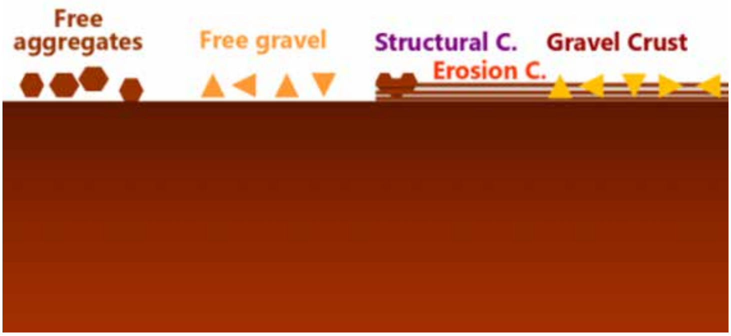

Figure 2.1. *Free aggregates and coarse elements, structural crust (embedded aggregates), erosion crust and gravel crust (embedded coarse fragments). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip*

Surface crusts are characterized in the field by their morphology: the nature and vertical succession of their microlayers, their thickness and porosity. Because of their very thin thickness, they are also examined in the laboratory using optical and scanning electron microscopes [VAL 92a] and, increasingly frequently, X-ray computed tomography imaging that allows 3D reconstruction [BAD 13, RIB 11]. Their hardness, or penetration resistance, is measured using penetrometers in either the field or in the laboratory [MON 14]. This hardness, expressed as resistance to penetration, opposes seedling emergence [GAL 07], and thus causes heterogeneity in the cultivated crop stand. The study of their process and formation factors is facilitated by the use of field [POD 08, RIB 11] or laboratory [MOR 14] rainfall simulators that reproduce the conditions of rain intensity, duration and height, as well as kinetic energy, similar to those of natural rainfall. Formation factors can also be derived from successive surveys on the same site or from map surveys. In order to predict the sensitivity of soils to disaggregation and therefore to crusting, numerous laboratory tests have been developed [AME 99, MON 14]. One of the most used in France is that of Le Bissonnais [LEB 96], which tries to reconstitute the main factors of structural crust formation.

2.2. Crust types and formation processes

2.2.1. *Structural crusts*

In order to predict their infiltrability, in other words, their infiltration capacity (section 2.4.1), it is important to distinguish several types of structural crusts [VAL 92a]:

– coalescing crusts: relatively thick (up to 1 cm), they form under a progressive settlement of aggregates that are already wet from the rain (section 2.3.2);

– infilling crusts: the fine silt particles detached by the rain on the surface of the aggregates and illuviation gradually fill the porosity between the aggregates;

– slaking crusts: they are formed during a sudden moistening of silty aggregates, due to the compression of air in the capillary porosity;

– packing crusts [RIB 11], which appear under the effect of heavy rains on microstructured tropical soils;

– sieving crusts, where the impact of raindrops on sandy soils causes a redistribution in microhorizons with the coarsest sands on the surface, fine sands in the middle and compacted fine particles at the bottom, trapping air vesicles (Figure 2.3).

Figure 2.2. *On the left: structural crust (ST), depositional crust (SED), facilitating the formation of a rill (R), silty soil developed from loess, Pays de Caux, France. On the right: microprofile of a coarse crust, coarse elements are embedded (G) in the crust punctuated by numerous vesicles (V), Tin Adjar basin, Gourma, Mali (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

2.2.2. *Gravel crusts*

They are defined by coarse fragments embedded in a structural crust [VAL 92b] (Figures 2.1, 2.2 and 2.7). Unlike free coarse fragments, they cannot be easily removed from the soil surface. In arid regions, these gravel crusts form desert paving, commonly called “desert pavements”. Like sieving structural crusts, these gravel crusts trap air vesicles (Figure 2.2), which reflect very low infiltrability (Figures 2.2 and 2.6).

2.2.3. *Erosion crusts*

These crusts are defined by their smooth surface aspect [VAL 92a]. They result from the erosion by water of structural crusts:

– silty or clayey: the roughness linked to the original aggregates disappears under the effect of compaction and runoff;

– sandy: the two sandy microfield surfaces are eroded by water and wind, leading to the exposure of the microhorizons where fine particles that are even more compacted by direct raindrop impacts are concentrated. In the latter case, very hard erosion crusts, which are very impervious, may be subject to sand blasting (Figure 2.4 and Chapter 3).

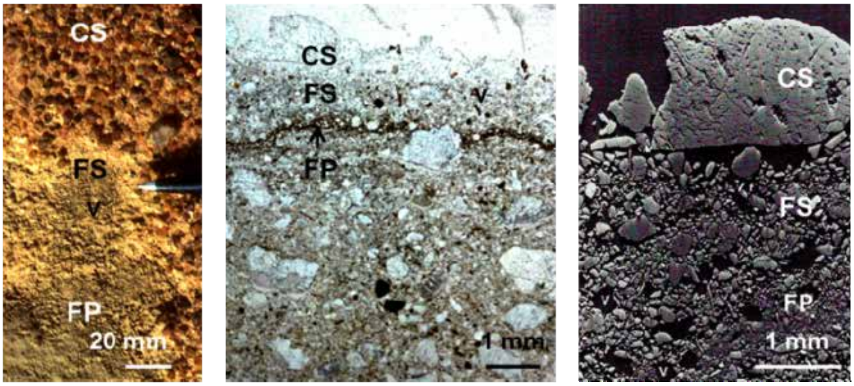

Figure 2.3. *Sieving structural crust. On the left, as seen from above, the microhorizons have been exposed with a brush: CS: coarse sand, FS: fine sand, FP: fine particles (<50 µm), v: air vesicle. Center: view on a vertical thin section. On the right: vertical view with a scanning electron microscope (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

2.2.4. *Depositional crusts*

There are three main types of depositional crusts as per the processes involved [CAS 89, VAL 92a]:

– runoff crusts: these are formed in a flow of runoff and are characterized by an alternation of microhorizons of contrasted grain size;

– sedimentation crusts: in non-turbulent water columns, according to Stokes' law, the coarser particles are deposited first, then the medium particles and lastly the finer ones. The result is a grain size distribution opposite to that observed in sieving structural crusts. This contrast of grain sizes leads to differential tensile strengths during desiccation, often resulting in cracks or even the appearance of curled up plates; this type of crust that forms in any puddle or pond has become iconic, but debatable, images of the media to illustrate the impact of climate change (Figure 2.4);

– wind: these crusts manifest themselves by vertical alternating microhorizons made up of fine particles (dust) and fine sand (generally around 100 µm).

Figure 2.4. *On the left: erosion crust (ERO) and runoff crust (RUN) subjected to strong wind erosion, at the foot of the Khongor dunes, Gobi Desert, Mongolia. On the right: sedimentation crust (SED), Banizoumbou, Niger (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

2.2.5. *Saline crusts and efflorescence*

This type of crust is discussed in Chapter 5 of this book.

2.2.6. *Biological soil crusts (or Biocrusts)*

For the past 20 years or so, most of the work on surface crusts has focused on the assemblage of many organisms (biofilms, cyanobacteria, mosses, lichens, etc.) that are cohesive enough with the upper soil mineral particles, to be also referred to as “crusts” [BEL 06]. In order to understand how they work, it is essential to know the substrate [BER 14, MAL 11] of these organisms: hard rocks that they help to weather, thus promoting pedogenesis, free particles or, as is most often the case in the driest regions, physical crusts. Indeed, the low infiltrability of physical crusts allows a certain accumulation of moisture on the surface, which facilitates their colonization by cyanobacteria which tend to consolidate them [MAL 11].

2.3. Crusting factors and principles for improving aggregate stability

2.3.1. *Soils*

No soil can withstand the direct impact of heavy rains for long. However, some soils are more vulnerable than others to surface crusts. Thus, the two main factors controlling the type of structural crust that constitute the first phases of crusting with the development of depositional, erosion and gravel crust are the silt and organic carbon contents (Figure 2.5).

Thus, the reduction in organic C content, linked to motorized monoculture without the addition of fertilizers or organic amendments, encourages the development of structural crusts, runoff and water erosion (Chapter 3), leading in turn to a depletion of organic C stocks. While organic matter consolidates aggregates, high levels of exchangeable sodium (Na) [ROB 01] and magnesium (Mg) [ZHA 02] are associated with soil aggregate stability. In addition, gravel crusts are more common in 2:1 clay regions (smectites), often drier than in regions with wetter kaolinitic soils where coarse elements remain free on the surface [VAL 94]. Type 2:1 clays provide less stable structures [LAD 04] than type 1:1 clays, which are larger and less swelling [NCI 16].

2.3.2. *Rain*

Surface disaggregation may result from the rapid wetting of silty soils (slaking structural crust). However, most of the time, structural crusts are formed by raindrop impact. The main factors to consider are the distribution of drop size, their impact velocity, and therefore their kinetic energy [LAC 15, PAT 11, VAL 87].

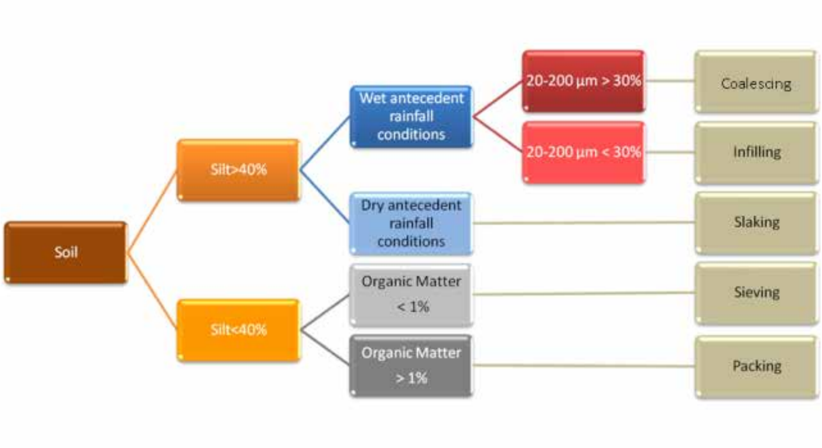

Figure 2.5. *Key for forecasting the types of structural crusts as a function of the total silt content of the sample, moisture conditions prior to rainfall, silt and fine sand content and organic matter (after [VAL 02])*

2.3.3. *Slope*

Due to the importance of the kinetic energy received, the slope angle influences crusting: it is all the more generalized when the slope is low, and therefore the kinetic energy received is high. This depends directly on the cosine of the rain/surface angle (1 for a zero angle – horizontal ground, 0 for a vertical slope). Thus, on very steep slopes, crusts are more difficult to form. This explains why runoff rapidly appears on soils with very low slopes, hence with maximum rainfall kinetic energy and thus easily encrusted (Figure 2.2), while infiltration predominates on very steep soils [RIB 11].

2.3.4. *Cover*

The different types of cover do not provide the same protection of the soil surface. They are all the more effective because they reduce the kinetic energy of the drops that fall through foliage. The main characteristics to be taken into account are the percentage of rain that reaches the ground after passing through foliage, which is called throughfall and the falling height, knowing that the maximum speed of the largest drops (5–6 mm) is only reached after 10–12 m because of air resistance. Thus, throughfall from this height may have a kinetic energy at least equal to that of the free-falling rainfall. This kinetic energy is most often higher, due to larger drops under plant cover than under free falling rainfall. Thus, tall trees do not protect the soil surface from disaggregation if the kinetic energy of the drops that pass through the foliage is not dissipated at a cover that is closer to the surface (undergrowth, litter) [LAC 15]. For an equal percentage of cover, a meadow or fodder [HA 12] will thus protect the soil better than a plantation of trees without undergrowth and litter (see Chapter 3, [PAT 12]).

2.3.5. *Agricultural practices*

Soil aggregate stability can be improved by organic and lime amendments [PAR 13], the latter being particularly useful for sodic soils. The degradation spiral: reduction of organic C content, crusting, runoff, erosion of organic carbon can be reversed by adding and maintaining organic C in the soil surface horizon by various inputs [FAT 06, PEN 16], including residues (Chapter 9). This can be achieved by intermediate or intercropping cultures, or by better weed management that can contribute to soil protection and organic status [DE 10].

Tillage has two antagonistic effects on crusting. On the one hand, it destroys the crusts, which is often indispensable in semiarid regions where these crusts prevent seedling emergence. On the other hand, tillage can promote the formation of crusts when it produces small aggregates that are destroyed more quickly than large clods. When preparing the seedbed, it is therefore important not to crumble the clods too much [GAL 07].

Because of the risk of silty aggregates slaking during their rapid wetting, water inflows by furrow irrigation must be frequent enough to avoid desiccation of the soil surface. The same applies to sprinkling irrigation, for which it must also be ensured that the pressure of the sprinklers, and therefore the impact speed of the drops, does not lead to the formation of surface crusts [VAL 87]. Part of the inflows would then be lost through runoff, which itself can cause erosion.

2.4. Consequences of surface crusting

2.4.1. *Hydrological: Hortonian flow*

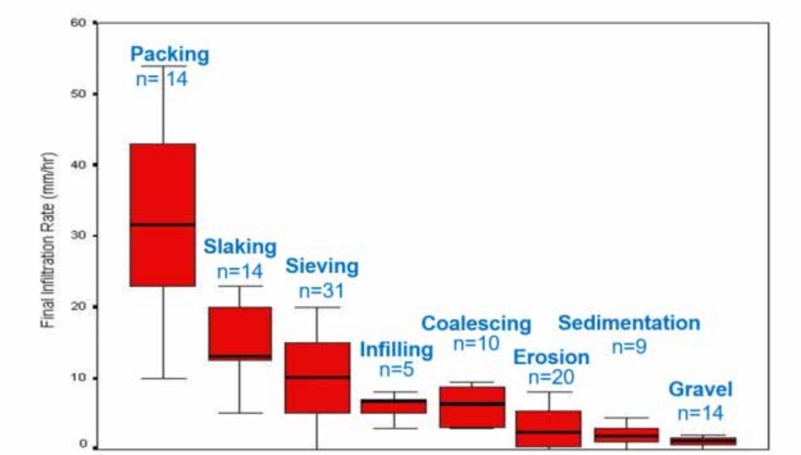

Figure 2.6. *Final infiltration intensity, measured under simulated rain for different types of crusts, from left to right: packing, slaking, sieving, infilling, coalescing, erosion, sedimentation and gravel crusts (after [VAL 02])*

Runoff occurs when soils are saturated with water to the surface. It is then a saturation excess overland flow, which can be particularly observed in humid temperate climates when water tables are raised to soil surface in winter near the streams. Most often, however, runoff is generated on slopes when rainfall has exceeded infiltration capacity. However, this Hortonian overland flow, according to R. E. Horton, one of the founders of hydrology, is controlled by the least porous surface horizons: crusts and plough plan for example. In many cultivated situations [PAT 12], fallow land [VAL 04], pastures [HIE 99], and even under planted forests [LAC 15] or in the natural environment [VAL 92a, VAL 99a], this infiltrability is first constrained by the infiltrability of crusts [CAS 92, PAT 12]. This varies considerably depending on the type of crust, ranging from just over 30 mm h^{-1} for packing structural crusts to only 10 mm h^{-1} for sieving structural crusts (on sandy soils), 8 mm h^{-1} for coalescing or infilling structural crusts (on silty soils), and only 1 mm h^{-1} for gravel crusts (Figure 2.6). This explains why runoff and water erosion (Chapter 3) can even occur under very low slope conditions and at low intensities, both in the loess plains of the Paris basin (Figure 2.2) and on Sahelian fixed dunes (Figure 2.7). Consequently, long droughts in the Sahel have led to a reduction in vegetation, an extension of surface crusts and a sharp increase in runoff [CAS 89] and the surface area occupied by ponds [GAR 10]. The strong runoff has also concentrated itself in sand bottomed gullies and nourished water tables, which raised during droughts [LED 01]. The gravel crusts, and in particular the “desert pavements” of desert regions, generate very high volumes of runoff at the slightest rainfall because of their vast surfaces. “Flash” floods thus arise, which are all the more dangerous as they can suddenly occur far downstream from the areas that have received rainfall. Many campers and motorists in very dry wadis find themselves surprised when a devastating flood wave suddenly submerges these dry river beds [FOO 04] (Figure 2.7).

Figure 2.7. *On the left: overland flow on a fixed dune, due to sieving structural crusts, northern Burkina Faso. On the right: flash flood due to the gravel crusts of the watershed, in the Gobi Desert, Mongolia (photos: O. Ribolzi, C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

2.4.2. *Ecological: example of the tiger bush*

Tiger bushes, and more broadly, banded vegetation formations in arid and semiarid regions, illustrate the essential role of surface crusts in water harvesting; the key to the functioning of these ecosystems [Val 99a]. These are defined as the spatial alternation of bare zones and bands of vegetation. Seen from an airplane, these “bushes” resemble the stripes of a tiger, hence their name (Figure 2.8; the angled aerial photo was taken 70 km east of Niamey, Niger). The downstream part of a band of vegetation is characterized by dead trees, sieving structural crusts and 80% runoff; the bare zone by erosion and gravel crusts, 90% runoff and an infiltration front less than 1 m; downstream of the bare zone by sedimentation crusts colonized by cyanophyceae, thus covered by biocrusts, and a surface accumulation of water and sediments; lastly, the band of vegetation by large trees in wetter regions, litter, high termite activity, no crust, annual infiltration of 95% and a wetting front exceeding 7 m (Figure 2.8, according to [GAL 99, LUD 05, VAL 99b]).

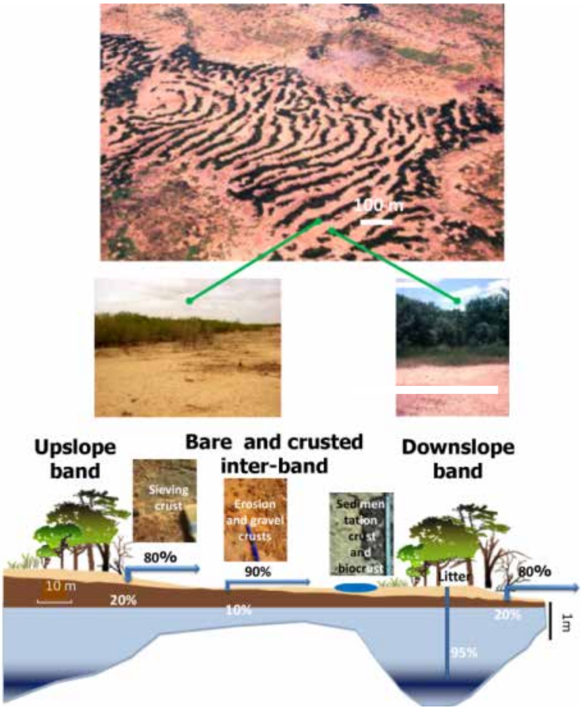

Figure 2.8. *Aerial view of a tiger bush, Niger. Detail of the state of surface, crusts, annual runoff percentage and infiltration depths (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip*

Thus, even for very slight slopes of less than 1%, a succession of crusts and vegetation can be observed in space, suggesting a progression upstream of these formations. Many approaches (dendrochrological, isotopic, etc.) have confirmed this slow migration (about 30 cm per year [Val 99b]), which demonstrates the power of recolonization and thus rehabilitation of bare crusted areas. This type of formation is based on the harvesting of runoff, which is generated by bare areas that act as an impluvium for the filled area downstream. It is very resilient to droughts because of the self-adjustment of the ratio of bare area/filled area according to the rainfall of the last 15 years, but is not very resistant to land clearing [Val 99a].

2.4.3. *Agronomic: water harvesting*

As the previous example has just shown, surface crusts are thus one of the essential components of ecosystems in arid and semiarid regions. They allow rainwater to be collected on more or less extensive surfaces (sources) and concentrated in privileged infiltration zones (sinks) [ROC 97] where, once stored in the soil, they will escape evaporation more than in reservoirs. In these regions, rainfall is insufficient in quantity and too concentrated over time to ensure continuous vegetation cover. Therefore, bare upstream zones used for runoff collection for downstream areas of vegetation should not be planted. In particular, agronomists and foresters, often quick to seek uniform stands, must take this necessary spatial heterogeneity into account. Drawing on the example of the tiger bush, they can also learn from practices at various levels. Figure 2.9 provides two examples of optimal surface crust management: erosion crusts can themselves facilitate their own rehabilitation by the *zaï* technique [FAT 06]: crops or woody plants are planted in holes into which organic manure is brought. This concentrates water and nutrient resources. The large runoff produced by gravel crusts in subdesert areas can be captured by earth and micro-dams that also retain sediments produced by gullies and thalwegs [SEN 13]. Thus, agricultural production (olives, almonds and even hard wheat) is possible under very low rainfall (Figure 2.9 showing the example of Jessour in southern Tunisia). South African agronomists have well understood that in a semiarid environment, the distribution of cultivated plants must be heterogeneous, alternating between planted rows and rows left bare [WOY 06]. Reforestation programs for very deserted plateaus in Niger are inspired by the example of the tiger bush pattern of planting in strips, leaving large bare encrusted areas between these strips.

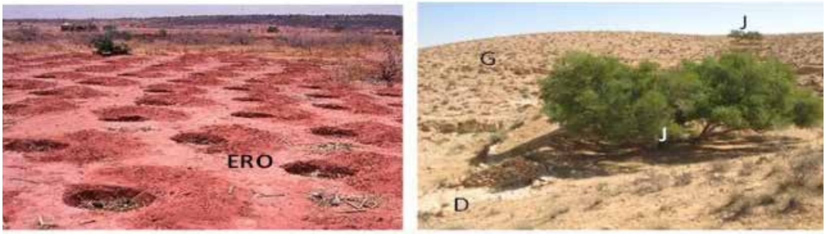

Figure 2.9. *On the left: organic manure-enriched pits (zaï) to rehabilitate soil covered with erosion crust (ERO), Banizoumbou, Niger, annual rainfall 550 mm. On the right: succession of "jessour" (J) along a thalweg, with a spillway (D), draining a basin covered with gravel crusts, Matmata mountains, southern Tunisia, annual rainfall 240 mm (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip*

2.5. Conclusions

Surface conditions constitute a kind of epidermis within the critical zone that controls exchanges among soils, vegetation and the atmosphere. In particular, crusts largely determine the proportion of precipitation that infiltrates the soil, and can constitute reserves for roots or supply the water tables, and that which runs off, the fate of runoff itself being determined by the distribution of surface conditions downstream.

Although still largely ignored by most hydrological and evaporation models, the different types of crusts make it possible to illuminate a certain number of paradoxes, such as strong runoff on very shallow slopes, on sandy soils or very dry and desert soils. The underlying physical crusts also explain why biocrusts may be associated with low infiltrability. While physical crusts generate runoff and often undesired water erosion, particularly in temperate and humid tropical regions, they are an essential component of semiarid and arid ecosystems. Soil and water management in these dry regions must take into account the necessity to maintain the heterogeneity of surface conditions between source, bare and crusted zones used for water harvesting and sinks that benefit from the concentration of water and sediment resources, and thus allow vegetation development.

RESEARCH QUESTIONS.–

1) What are the interactions between biocrusts and the environment on which they develop: rocks, well-structured soils and physical crusts, and what are the consequences for the weathering/erosion balance (water and wind), the storage of water, organic carbon and nitrogen [BER 14]?

2) To what extent are contaminants concentrated on the soil surface, particularly within the crusts, and for how long [MAL 14]?

3) What are the best practices (tillage or non-tillage, types of soil amendments, etc.) to ensure higher aggregate stability [PEN 16]?

RECOMMENDATIONS.–

1) Maintain permanent cover directly over, or at very low heights above, the ground surface in temperate and humid tropical regions in order to limit the kinetic energy of rainfall (and sprinkler irrigation).

2) Avoid soil surface crumbling during seedbed preparation and maintain or even enhance soil organic status (biomass production and soil amendments).

3) Maintain bare crusted zones in arid and semiarid areas in order to allow water harvesting and concentration of resources in patches or bands of vegetation.

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