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THE ROLE OF THE MINERAL COMPONENT IN SURFACE STABILIZATION PROCESSES OF A DISTURBED DESERT SANDY SURFACE

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ABSTRACT

The stabilization of sandy and loamy surfaces in semiarid and arid areas by topsoil crusts protecting the soil against wind or runoff erosion is well known. Destruction of such crusts, often by overgrazing, can enhance erosion and desertification. Crust recovery does not depend purely on biotic components of the crust and vegetation. Mineral components in the initial surface stabilization process are often overlooked. The present study focuses on the relative importance of the biotic and mineral components in the process of topsoil crust recovery in a sandy desert area located in the northwestern Negev Desert of Israel. Observations of the initial crust and of the disturbed surface, in the field and under the scanning electron microscope, showed that the mineral components of the crust recovered more quickly than its biotic elements. The implications for the rehabilitation of the disturbed ecosystem are discussed.

KEY WORDS: sandy desert areas; topsoil crusts; crust recovery rate; surface stabilization; biotic and mineral components

INTRODUCTION

Biotic crusts have become recognized as essential components of surface stability and productivity in arid and semiarid areas, and the issue of crust recovery, following crust destruction, has attracted the attention of many desert ecologists (Belnap *et al.*, 2001). Two essential aspects are discussed in the literature. The first is the recovery rate of disturbed surfaces that varies in a very wide range from 5 to 250 years (reviewed in Belnap and Eldridge, 2001), depending on the type of disturbance, soil properties, water regime and biological components of the crust. The second aspect refers to succession stages in the recovery process. The present work focuses on the latter in a sandy area located in the northeastern Negev Desert.

The views on succession are a matter of controversy. The pioneering role of cryptogams in primary and secondary plant succession in arid and semiarid areas is supported by several authors (Booth, 1941; Metting, 1981; Rayburn *et al.*, 1982; Mazor *et al.*, 1996). Danin *et al.* (1989) proposed that the establishment of pioneer grasses, following rainy days, precedes the rapid establishment of filamentous cyanobacteria and the formation of the biotic crust. Subsequently, accumulation of airborne particles rich in nutrients facilitates the establishment of higher plants. Tsoar *et al.* (1995) adopt a more extreme position and contend that biogenic crusts are formed when vegetation cover reaches about 20–30 per cent. Vegetation and biogenic crust then act as traps for aeolian material.

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Ecologists or botanists tend to concentrate on biotic aspects such as occurrence of cyanobacteria, lichens and mosses (Anderson *et al.*, 1982; Johansen, 1986; Belnap, 1995) or chlorophyll and sugar content (Mazor *et al.*, 1996) and may overlook the mineral component in the surface stabilization process which requires a fast deposition rate of fine-grained particles sticking to the surface of the sand and promoting the development of a well-cemented topsoil crust that stabilizes the surface. As the deposition rate is highly dependent on the availability of fine-grained aeolian particles and on the local wind regime, the role of the mineral component in surface stabilization can vary greatly throughout arid and semiarid areas. The depositional topsoil crust described above differs from crusts that result from waterpooling and suspending of fine-grained particles, such as commonly occur in the shallow sandy soils on the Colorado Plateau (Belnap and Gardner, 1993). The depositional crust also differs from topsoils crusts that develop in fine-textured soils due to the dispersion of fines by raindrop impact.

This study focuses on the relative importance of the biotic and physical components in the process of crust recovery in a disturbed sandy desert area.

THE STUDY AREA

The study was conducted in the Nizzana sand field at the eastern extension of the Sinai continental erg (Figure 1). Average annual rainfall is about 90 mm with a high annual variability. Average monthly temperatures are 9°C in January and 25°C in August (Rosenan and Gilad, 1985). Potential annual evaporation is in the order of 2200 mm (Zangvill and Druyan, 1983). The rainy season is limited to the winter months, extending from October to May. A geomorphic analysis of the linear dune system (Yair, 1990) shows a subdivision into two main units (Figures 1 and 2):

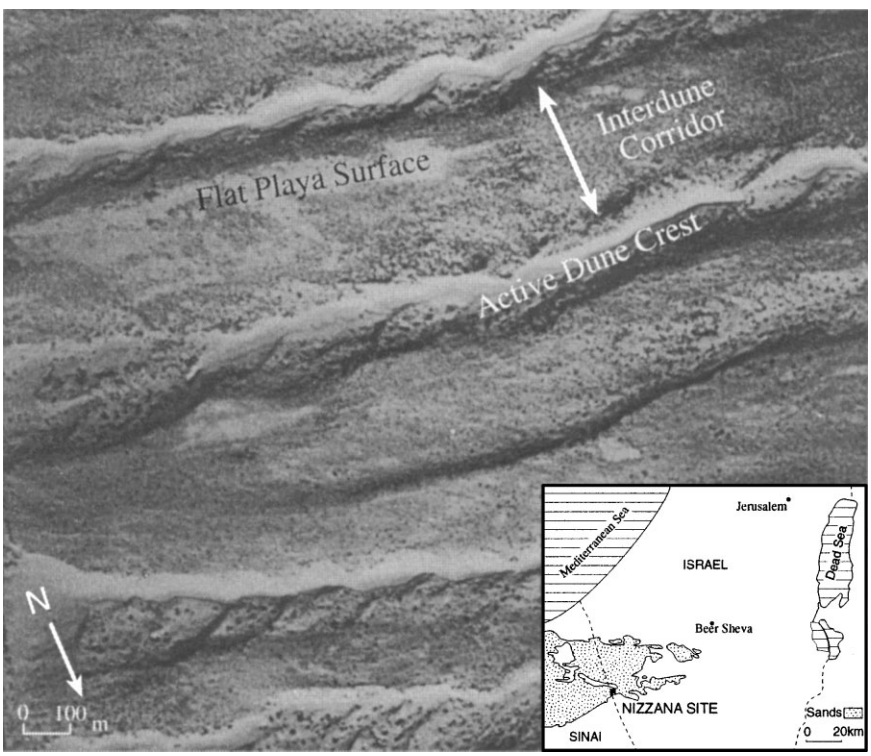

Figure 1. Location and view of the dune system.

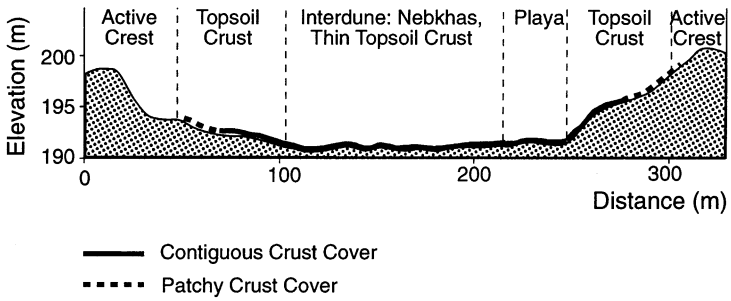

Figure 2. Geomorphic units across the dune system; dotted line: discontinuous topsoil crust; bold line: continuous crust (playa excluded).

(1) *The sandy ridge* (Figure 1). Its crest is devoid of a biotic crust and the vegetal cover is sparse. Well-developed ripple marks clearly indicate that the crest is highly unstable and sensitive to wind. A biotic crust, brown grey in colour, covers the steep flanks of dune ridges. The thickness and continuity of the crust, as well as the cover of vascular plants, increase downslope. Ripple marks are absent where the crust is most developed, indicating that such stable surfaces are not sensitive to wind activity. Due to differences in the microclimate, the crust and the woody vegetation are better developed on north- compared with south-facing slopes (Kidron and Yair, 1997). The crust is dominated by cyanobacteria and also contains green algae and mosses (Lange *et al.*, 1992). The topsoil crust contains up to 40 per cent silt and clay, as compared to 3–7 per cent in the underlying unconsolidated sand (Yair, 1990).

(2) *The interdune corridor* (Figure 1). This covers some 60 per cent of the area and has a complex topography of low sandy ridges, hummocky vegetated sandy surfaces and horizontal fine-grained layers of flood sediments deposited by the nearby Nizzana Wadi (Harrison and Yair, 1997). A thin biological crust, lighter in colour than the crust observed on north-facing slopes, is developed on the sandy surfaces.

METHODOLOGY

Field Experimental Layout

Crust regeneration was monitored on 21 plots from where the crust had been completely removed. Observations by Campbell (1979) show that microbial elements are found to a depth of up to 5 cm within the soil and move towards the surface upon wetting. In order to eliminate the possibility of crust recovery due to this vertical migration from below the surface a topsoil layer 10 cm thick was removed, even when the crust is only 1–2 mm thick, thus creating a disturbed bare and unconsolidated sand surface. The plots were bordered by metal sheets (Figure 3) inserted 10 cm into the sand. The closed plots served as sediment traps for airborne falling particles and prevented inoculation from the adjoining crusted areas. Plots were established on north- and south-facing slopes, as well as in the interdune area. Rainfall and wind speed were recorded by permanent devices in operation in the study area.

Sampling Programme

The monitoring period lasted three rainy seasons (1996–99). Prior to the removal of the topsoil layer a representative sample of the undisturbed crust was taken from each of the plots. The plots were sampled again immediately after the removal of the topsoil crust. Afterwards, sampling for particle size analysis was conducted twice a year, at the beginning and end of the rainy season. Particle size analysis provides some data on the deposition rate of silt and clay within the disturbed plots. Such deposition is assumed to enhance stability conditions and development of the living components of the crust. Samples for the analysis of crust development were taken from the original undisturbed crust and at the end of the third rainy season. Samples were always taken from the same reference site within each plot.

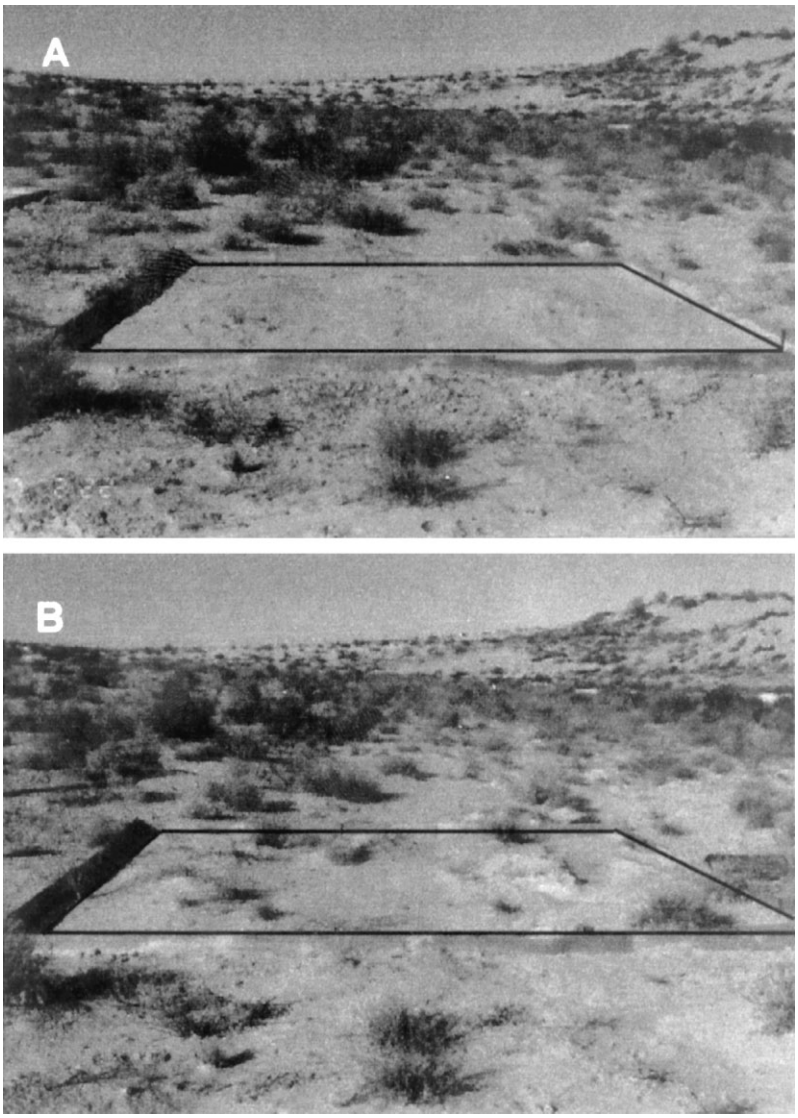

Figure 3. View of monitoring plots; A: following the removal of the topsoil crust and vegetation cover; B: view of the initial surface.

LABORATORY ANALYSIS

Before processing in the laboratory the thin and fragile topsoil crust was delicately separated from the underlying sand. With time, the separation of the stable topsoil crust from the loose underlying sand became easier. Analysed samples represent the three main characteristic environments of the study area: the base of the north- and south-facing slopes and the sandy interdune. Samples were submitted to the following analyses.

Grain size distribution

Grain size distribution was conducted on samples, dispersed with sodium pyrophosphate, by two methods. The visual accumulation tube for the sandy fraction and the sedigraph for the silty and clayey fractions.

Electron microscope photography

An environmental scanning electron microscope (ESEM XL 30 Philips®) was used in order to make visible the degree of development of the biotic and mineral components of the topsoil crust. The magnification varied in the range of 1:350 to 1:650. Each sample was scanned twice with views of (1) the topsoil surface and (2) the material immediately below the thin topsoil surface. The thickness of the scanned samples was $\sim$1 mm.

RESULTS AND DISCUSSION

Rainfall Regime

The monitoring period was characterized by dry to very dry years (Figure 4). Annual rainfall in 1996–97 amounted to 73·2 mm with three distinct rainy periods. The first rainy period lasted from October to December 1996. Rainstorms were sporadic with small rain amounts; the total rain amount, recorded in six storms, was only 7·9 mm. The second rainy period lasted from January 14 to February 4 1997 with a total rainfall of 54·8 mm. The third period lasted from February 22 to April 2 1997, with numerous small storms.

The second year (1997–98) rainfall started on the second half of October 1997 and ended in March 1998. Annual rainfall was similar to that of the previous year (71·8 mm). Most of the rainstorms were less than 5 mm. The largest single storm (20 mm) was recorded on 11–12 January 1998. The end of the rainy season was characterized by few rainy days with rain amounts up to 2·4 mm.

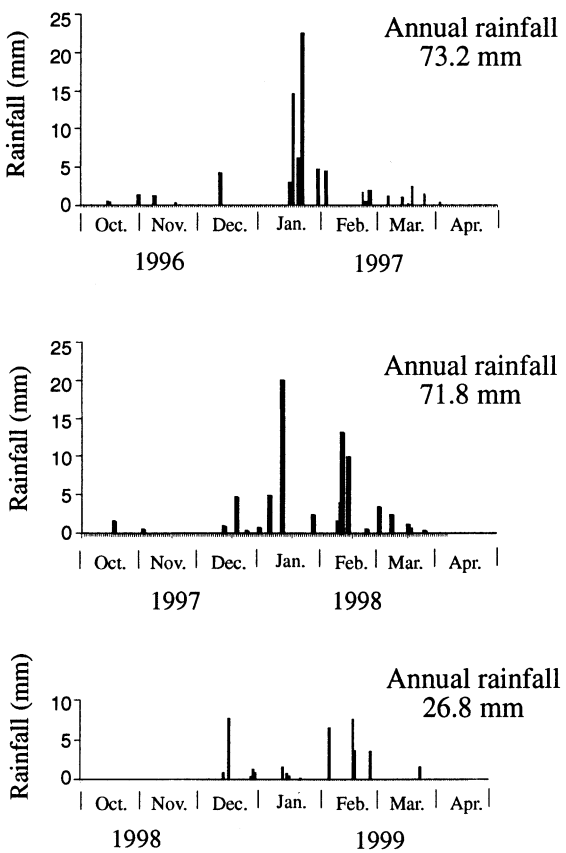

Figure 4. Rainfall regime: 1996–99.

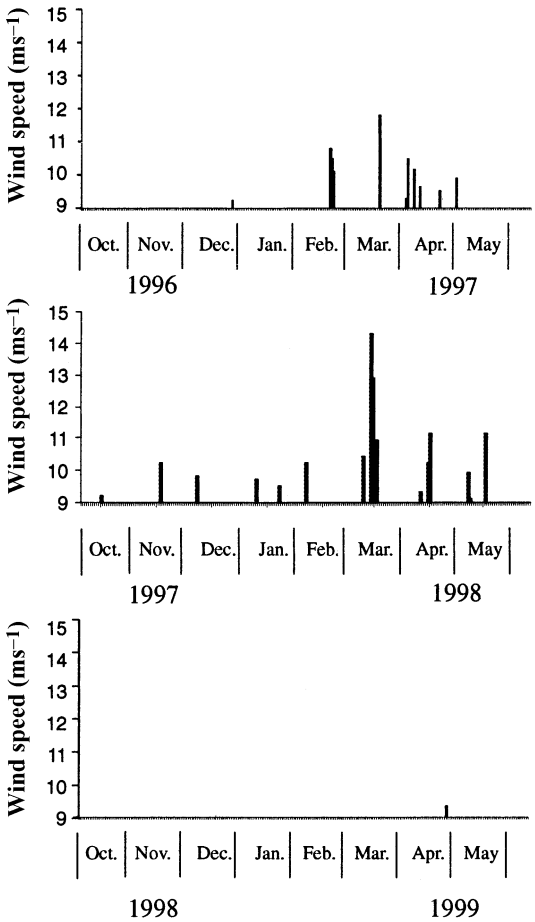

Figure 5. Wind regime: 1996–99.

The third year (1998–99) was the driest. Annual rain amount was only 28·5 mm. Rain started late in the season (mid-December) and ended in March. Most storms were below 2 mm. Half of the annual rainfall was recorded on 19–20 February 1999.

Wind Regime

Strong to very strong winds are expected to limit or even prevent crust regeneration over a disturbed, unstable, sandy surface (as shown by the total absence of the crust at the crest of sandy ridges where strong winds prevail). The temporal changes in wind velocity during the research period are displayed in Figure 5. Velocities above $9\,m\,s^{-1}$ are high enough to detach and move the medium to fine sand grains forming the dunes in the area.

Winds in excess of $10\,m\,s^{-1}$ were recorded in 1996–97 only towards the end of the rainy season, especially on 21 March 1997 ($42\,km\,hr^{-1}$), after the major rainy spell of January. Wind velocities higher than $9\,m\,s^{-1}$ did not occur in the study area during the summer and autumn seasons.

The frequency of winds in excess of $9\,m\,s^{-1}$ was higher in 1997–98. Strong winds, more than $9\,m\,s^{-1}$ occurred in the area from October 1997 to May 1998. March 1998 was especially windy with wind velocities of up to $14{\cdot}5\,m\,s^{-1}$ and substantial amounts of sands were transported into the area. As in the first year, strong winds in excess of $9\,m\,s^{-1}$ were not recorded during the summer and autumn seasons.

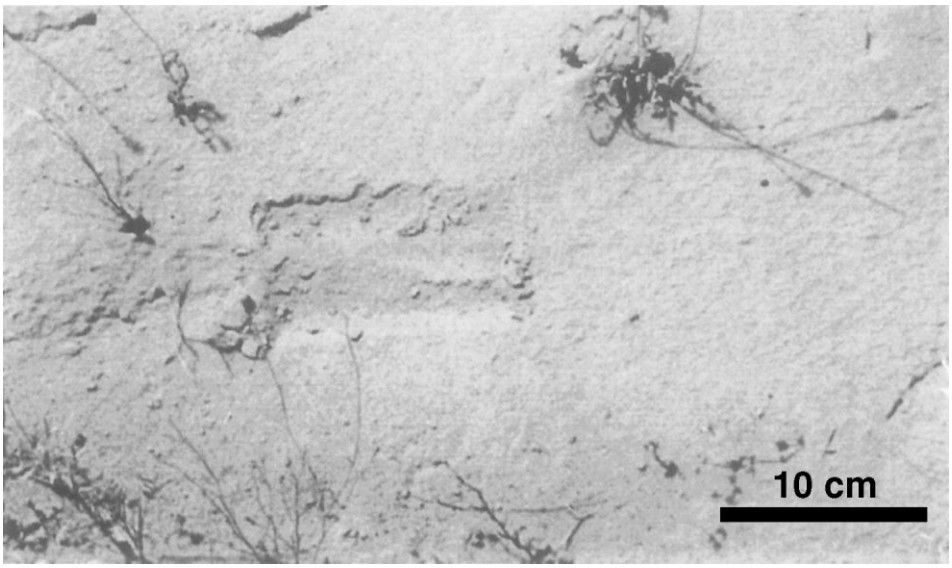

Figure 6. Stable yellowish crusted surface with no ripple marks (May 1998).

The third year was characterized by weak to very weak winds. Winds in excess of 9 m s^{-1} were recorded only once, in April 1999.

TOPSOIL CRUST REGENERATION

Field observations

The removal of the crust from monitoring plots took place in September 1996. Field observations a month later showed that winds strong enough to remove sand particles occurred in the area, before the first rain, resulting in the development of ripple marks over all plots. The ripple marks persisted during the following summer and autumn seasons, although a very fragile topsoil crust was observed over limited parts of the plots, at local depressions within the ripple marks. Two interesting and significant field observations were made in May 1998, at the end of the second year. Despite the very strong winds, and massive sand transport, which prevailed in the area in March 1998 (Figure 5) the topsoil crust that had developed by the end of two rainy seasons was not destroyed, being resistant enough to strong winds. The high resistance of the topsoil crust was furthermore indicated by the lack of ripple marks over most of the originally disturbed surface (Figure 6). The yellowish colour of the new topsoil crust was much lighter than the dark colour of a well-developed original topsoil crust, pointing at a low organic matter content in the newly developed crust. The pale and resistant yellowish crust persisted throughout the third rainy season, which was characterized by very dry conditions and weak winds.

Mineral aspect of topsoil crust regeneration

As indicated earlier, a well-developed biological topsoil crust is rich in fines. The amount of silt and clay in the original crust, before its removal from the plots, was 33 per cent at the base of the north-facing slope; 32 per cent in the interdune area and 23 per cent at the base of the south-facing slope. Following the removal of the topsoil crust in September 1996 the percentage of fines at the new disturbed surface was much lower, and varied in the range of 2–6 per cent. Table I presents the temporal variation in silt and clay content of the new topsoil crust at north- and south-facing plots. Figure 7 displays the grain size distribution of the original topsoil crust before its removal, and that of the regenerated topsoil crust by the end of the third rainfall season, in March 1999.

A sharp increase in fine particles, especially silt, was observed over all plots following the rainy spell of January 1997. The next samples for particle size analysis were taken in October 1997, before the first rains of the following

Table I. Temporal changes in silt and clay content (%)

Date	10·9·96	11·9·96	27·1·97	23·10·97	23·10·98	28·3·99
North	32·4	2·9	9·3	3·5	26·7	18·5
South	22·9	1·8	11·8	5·3	18·3	22·5

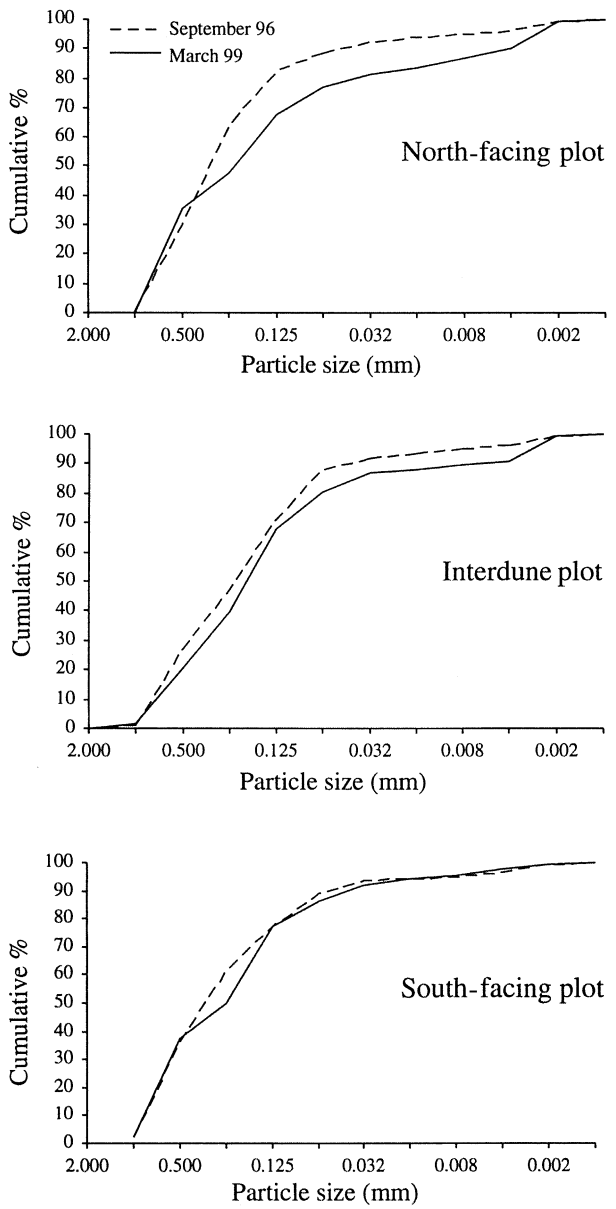

Figure 7. Particle size distribution before the removal of the crust and after three years.

rainy season. A decrease in fine particles was observed (Table I). This decrease is attributed to the strong winds recorded in the area at the end of the first rainy season, in February–May 1997 (Figure 5). These winds destroyed the initial fragile fine-grained crust that had developed earlier and increased the development of ripple marks all over the plots. Silt and clay content were, however, slightly higher in October 1997 than immediately after the removal of the topsoil crust on September 1996. A significant increase in silt and clay content occurred by the end of the second year, and persisted until the end of the monitoring period. The high amount of fines probably accounts for the high resistance and stability of the topsoil crust during the strong to very strong winds recorded in the area in March–May 1998. By this time ripple marks were absent from most of the area within the plots (Figure 6).

The rapid recovery of the mineral component of the topsoil crust does not support the view expressed by many authors that the early establishment of the living components of the topsoil crust precedes and preconditions the deposition of fine-grained particles that enhance sand stabilization. A substantial perennial vegetation cover did not develop within the plots by the end of the monitoring period. The rapid deposition of fine-grained particles in monitoring plots contradicts the findings by Littman (1997) who worked in the same area and contends that the recovery of the mineral components of the crust would require a time span of 100–300 years. His findings are based on dust collection in collectors set at 1 m above the surface, whereas in the present study the rate of dust deposition is based on samples collected directly from the surface. The latter method seems to provide a more reliable way to estimate the deposition rate of fine-grained particles in the area.

Scanning electron microscopy

This method provides an independent way to analyse the relative importance of the mineral and biological components in the process of topsoil crust recovery and surface stabilization. Figure 8 displays the view of the top mm of a well-developed, undisturbed, topsoil crust. A dense network of filaments (Figure 8A) composed of cyanobacteria and lichens (Figure 8B) can be observed. The mineral matrix is composed of sand grains and fine particles. The compaction and cementation are low due to many large voids (Figure 8C). This open structure explains the high to very high initial infiltration rates recorded in the area (Yair, 1990; Kidron and Yair, 1997).

Figure 9 shows a typical crust collected in March 1999. In the upper layer of the crust (Figure 9A), biological elements are rare and can hardly be seen. The sand grains are embedded in a dense and compacted smooth matrix of fine-grained particles. The number and size of voids are very limited in comparison with those observed in Figure 8C. Figure 9B shows the lower part of the same sample. Some filaments of fungi can be observed, though cyanobacteria and lichens are still absent. This lower layer of the crust is predominantly composed of sand grains and almost completely devoid of fine-grained particles. The structure is very open with many large voids.

The analysis of the electron microscope photographs fully support the earlier conclusion that the physical components of the crust develop more rapidly than the living components. It provides good evidence that the main process responsible for surface stabilization in the study area is the rapid deposition of fine-grained particles that creates a well-compacted thin surface layer, thus limiting wind activity. The resistant and compacted surface was observed after only two years following the removal of the original crust.

The implications of the results for the rehabilitation sequence of a disturbed sandy arid ecosystem are complex. It appears that the regeneration process occurs at two different time scales, each related to the physical and biotic aspects of the crust. The rapid deposition of fine-grained material leads to a rapid stabilization of the disturbed surface. This process may be regarded as a positive phenomenon that provides the necessary conditions for the establishment of microbial life and higher plants. However, the development of a compacted physical crust may also have a negative effect on the recovery of the vegetation, as such crusts can reduce water infiltration, thus inhibiting root penetration and germination. The negative effect of the physical crust on the ecosystem may be enhanced by the limited and slow recovery of the biotic elements of the topsoil crust. It is well known that biotic soil crusts help maintain the fertility of arid ecosystems by contributing both nitrogen and carbon and by providing a food source for other web components (Belnap, 2001).

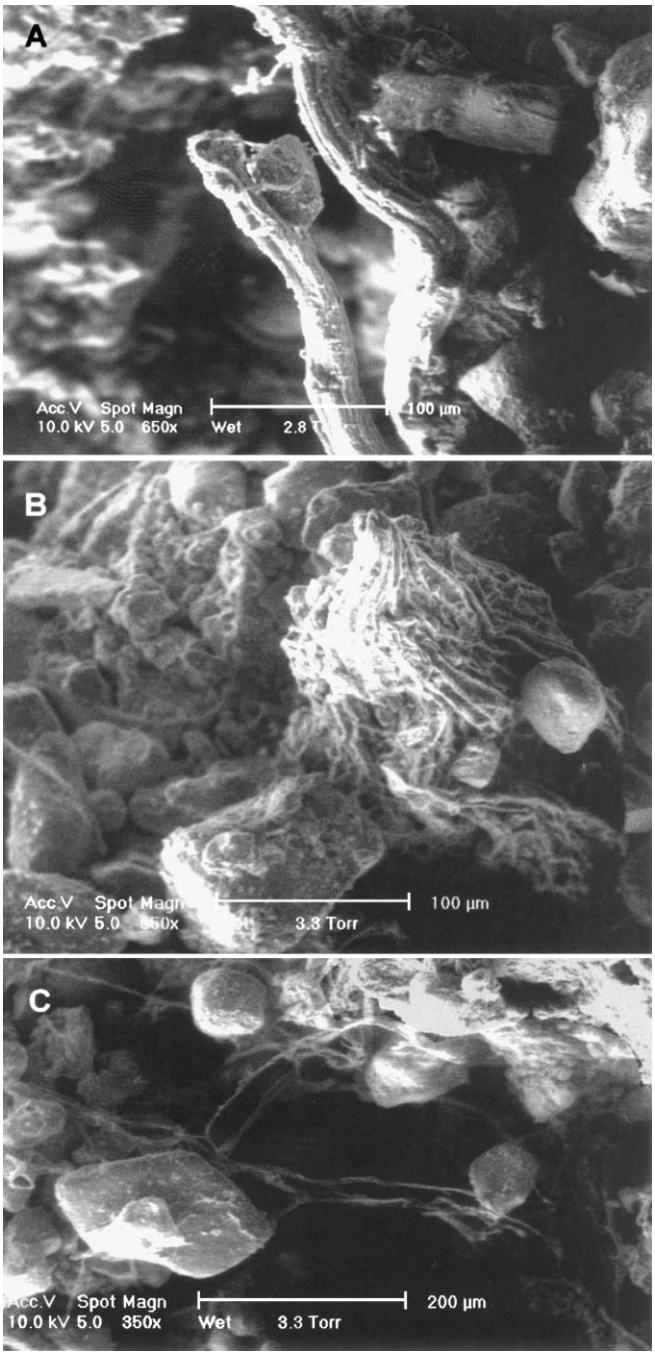

Figure 8. ESEM views of the well developed initial crust: A. cyanobacterial sheath; B. lichen; C. fungal filaments in the open structure beneath the surface layer.

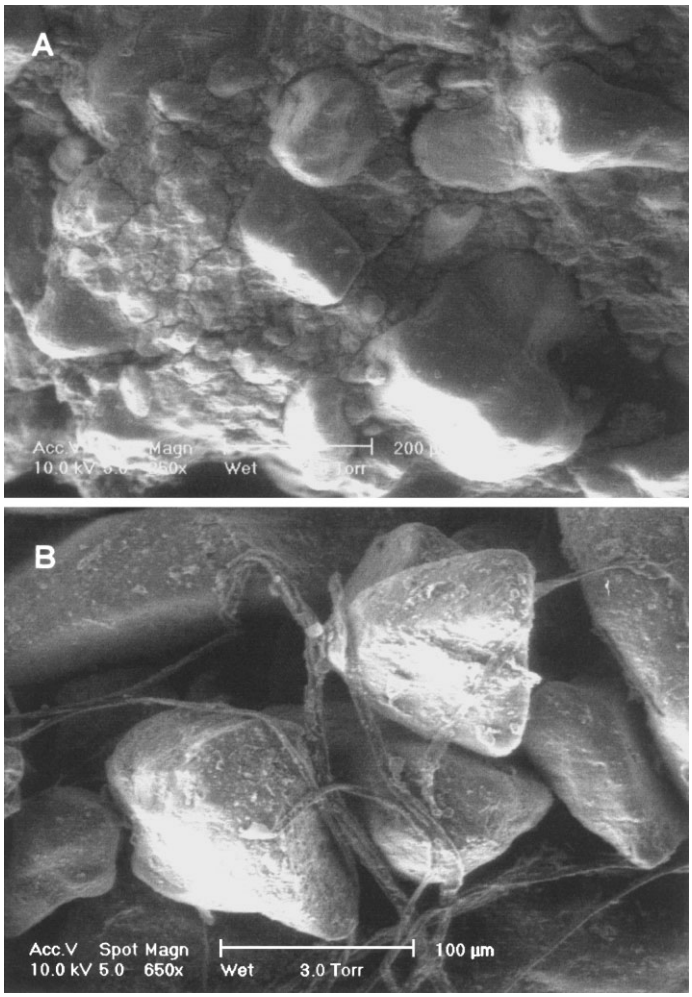

Figure 9. ESEM view of the topsoil crust after 3 years; A: surface layer: sand grains embedded in a compacted dense matrix of fine grained particles; B: subsurface layer—open structure composed only by sand grains trapped in a slightly developed fungal filaments network.

CONCLUSIONS

The present study, on the regeneration processes and rates of a disturbed sandy area, spanned three consecutive rainy seasons. During each season, especially the last, annual rainfall was below average. Strong winds in excess of $9\,\mathrm{m\,s^{-1}}$ prevailed in the area during the first and second monitoring years, but not during the last year. Data obtained lead to the following main conclusions:

(1) In the case of the Nizzana sand field, stabilization of disturbed surfaces was extremely rapid. The topsoil crust that developed by the end of two rainy seasons was stable enough to resist strong to very strong winds that later prevailed in the area. Such a stabilization rate is much faster than rates given in other studies.

(2) Particle size analysis shows that the recovery of the physical component of the crust is quite fast in the Nizzana sand field. This conclusion is supported by the analysis of scanning electron micrographs. The samples of the topsoil crust taken in March 1999 show a thin surface crust that is dense and well compacted, with few biotic elements. It therefore appears that the rapid deposition rate of fine-grained particles represents the main factor in surface stabilization in the study area, preceding primary and secondary plant succession.

(3) The rapid surface stabilization observed in this specific study does not imply a full recovery of initial ecosystem properties. The new stable surface represents a less fertile ecosystem than the initial one as it lacks the important contribution of the living elements to the ecosystem. These elements are known to serve as a food source for other food web components and as a source of nitrogen and carbon. Our results suggest that any study of topsoil crust regeneration should consider both the physical and biotic components of the crust. The recovery rate of these two components is not uniform in the rehabilitation process. It may be expected to vary in a wide range as a function of numerous factors such as the local wind regime, the deposition rate of fine-grained particles, the type and degree of disturbance, and finally the moisture regime that represents the most limiting factor for the regeneration of the biotic elements.

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