Chapter 14

Crust and dust

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This chapter has two parts: The first part, entitled "Biogenic Soil Crusts Enhance Runoff Production in the Northern Negev Desert" (by Eli Zaady, David J. Eldridge and Moshe Shachak), deals with the soil surface in desert ecosystems and relates to the effect of soil surface crust on desert hydrology. The second part, entitled "Applicative Methods for Aeolian Particle Study in Desert Environments" (by Zvi Y. Offer and Eli Zaady), deals with aeolian dust dynamics and relates to field research methods, used in the Negev desert, to analyze particle size distribution, micromorphology and chemistry. These subjects are applicable to similar environments worldwide.

Biogenic Soil Crusts Enhance Runoff Production in the Northern Negev Desert

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Introduction

The landscape of the northern Negev desert of Israel is predominantly natural shrubland comprising two biotic patch types: shrubs and biogenic soil crust (BSC) communities (Evenari, 1985; West, 1990; Shachak, Sachs and Moshe, 1998). In the Negev region, the crust could be of biogenic origin (BSC; West, 1990), or of physical-chemical origin (e.g. depositional crusts; Eldridge, Zaady and Shachak, 2000). A BSC is characterized by a tightly structured surface (Fletcher and Martin, 1948), colonized by a complex community of mosses, lichens, soil algae, fungi, cyanobacteria and soil bacteria (Friedmann and Galun, 1974; Skujins, 1984; West, 1990; Johansen, 1993.). This "cryptogamic" or "microphytic" crust community varies markedly from relatively homogeneous 2–3-mm thick cyanobacterial crusts to very complex crusts 15 mm thick. Homogeneous crusts occur in the central Negev in areas that receive 75–125 mm average annual rainfall, while complex crusts occur in the northern Negev in areas that receive 200–300 mm average annual rainfall (Zaady, Gutterman and Boeken, 1997).

There is some confusion about the role of BSC in infiltration processes (Yair, 1990; Belnap, 2006). Well-developed BSCs found in dry regions around the world are hydrophobic, due to the gels and polysaccharides secreted by their constituent microphytes—cyanobacteria and soil algae (Mehta and Vaidya, 1978; Bertocchi, Navarini and Cesaro, 1990; De-Philipis et al., 1993)—and the mucilaginous sheaths these exude directly onto the soil surface. This mucilage binds the soil surface particles (Baily, Mazurak and Rosowski, 1973; Metting and Rayburn, 1983), making them effective at preventing soil erosion by wind and water (West, 1990; Gillette and Dobrowlski, 1993; Belnap, 1995; Belnap and Gillette, 1998; Eldridge, 1993). The cyanobacteria track water and light in desert soils and move upward within the soil surface (Garcia-Pichel and Pringault, 2001). Brotherson and Rushforth (1983) and Greene, Chartres and Holdgkinson, (1990) reported that BSC enhances water infiltration. Studies in the northern Negev desert of Israel on loess soils have suggested that BSC often reduces infiltration (Zaady and Shachak, 1994; Eldridge et al., 2000) and thus might enhance runoff generation (Shachak et al., 1998).

In this article we report the results of a two-part study (two different spatial scales) that assessed runoff generation by and infiltration through BSC. In the first small-spatial-scale study we examined infiltration through crusts in Petrie dishes (64 cm^2). We compared these results with observations from the second large-spatial-scale study of natural rainfall (0.5 m^2) and rainfall simulation (1 m^2) *in situ* on field plots. Our **objective** was to explore the relationship between BSC and water flow through (infiltration) and across (runoff generation) crusted surfaces in the northern Negev. Our **hypothesis** was that crusts retard infiltration and enhance runoff of water, and that this phenomenon is consistent across a range of spatial scales. We tested this hypothesis by measuring 1) infiltration through small cores of intact crust under laboratory-induced rainfall, and 2) runoff from *in-situ* crusts using both natural rainfall and artificial rainfall.

Study site

The field-based studies were conducted at the Long Term Ecological Research Station (LTERS) (Gosz, French and Sprott, 2000) at Sayeret Shaked (31°17' N, 34°37' E), located 150 m above sea level in the northern Negev near Beer Sheva, Israel. The landscape of this 2-km^2 area, closed off from grazing livestock since 1987, consists of low hills. The average daily minimum temperature in winter is 6–8 °C; the average daily maximum temperature in summer is 32–34 °C (Stern et al., 1986). Most rainfall events in this semiarid region occur between November and March. Long-term average annual rainfall is approximately 200 mm (the 200-mm isohyet forms the transition zone between arid and semiarid deserts in Israel; Bruins, 1990) (see Table 14.1).

The loess soil, composed of 14% clay, 27% silt and 59% sand (USA classification: loess soil with sandy loam texture – Calcixerollic, Xerochrepts) is up to 1 m thick and sits atop Eocene bedrock. The salt content of the upper 25 cm of soil is low, with an electrical conductivity of 0.4 dS m^{-1} (Teomim, 1990).

The soil surface is covered with BSC consisting of bacteria, cyanobacteria, algae, mosses and lichens (Zaady, Groffman and Shachak, 1996). Interspersed with the BSC are scattered patches of perennial shrubs. The dominant perennials in the research area are: *Asphodelus ramosus* (Liliaceae), *Thymelaea hirsuta* (Thymelaeaceae), *Noaea mucronata* (Chenopodiaceae), *Atractylis serratuloides* (Asteraceae) and *Pituranthos tortuosus* (Apiaceae) (Feinbrun-Dothan and Danin, 1991).

Soil covered with a well-developed BSC has a tightly structured surface (Fletcher and Martin, 1948). In contrast, the soil under patches of shrubs lacks a well-developed BSC, and its surface is covered with loose soil particles.

Table 14.1. Average annual rainfall (mm) and runoff production (liters m^{-2}) in plots with biogenic soil crust cover and calculated mean overland water runoff at the Sayeret Shaked Long-Term Ecological Research station, between 1993 and 2006

Rainy season	Average annual rainfall (mm)	Mean runoff (25.5%) (liters m^{-2})
1993-1994	97.5	24.9
1994-1995	285.0	72.7
1995-1996	108.0	27.5
1996-1997	200.0	51.0
1997-1998	177.0	45.1
1998-1999	68.6	17.5
1999-2000	89.6	22.8
2000-2001	189.1	48.2
2001-2002	150.8	38.5
2002-2003	176.7	45.1
2003-2004	158.1	40.3
2004-2005	282.8	72.1
2005-2006	148.0	37.7

Methods

Undisturbed samples of surface soil dominated by BSC were collected in 90-mm diameter plastic Petrie dishes and transported intact to the laboratory. The experiment consisted of a fully orthogonal design of three surface types: natural BSC, physico-chemical (compacted) crust, and loose (plowed) soil as control, each type was replicated 20 times. The BSC samples were oven-dried for 24 hours at 48 °C before commencement of the study. The physico-chemical soil crust samples were prepared by watering loose, crust-free soil, compacting it, and then rapidly oven drying it at 48 °C for 24 hours. Five 0.5-mm holes were drilled into the base of each Petrie dish and Whatman No. 1 filter paper was placed over the holes to prevent any loss of soil. Each of the samples weighed 80 g at the beginning of the experiment. The Petrie dishes were placed inside plastic tubes of the same circumference and sealed there with silicon rubber sealant to prevent water leakage. A 100-ml column of distilled water was added to each tube above the Petri dish (Maestre et al., 2002). Infiltration rates for each treatment were measured following application of the distilled water.

In the field studies, we tested whether runoff water was generated by BSC cover on the slopes of the watershed. Fifteen small runoff plots were established with internal areas of 0.5 m^2 on a BSC-dominated north-facing slope (7° inclination; Zaady, Levacov and Shachak, 2004). The plots were bound with sheets of PVC hammered into the soil to a depth of about 5 cm. A flume on the downhill side of each plot led to an 18-liter capacity runoff-water collecting device. The flume and the collector were covered to prevent raindrops from entering them from above (Zaady et al., 2004). After each runoff-producing rainfall event, the runoff found in the containers was collected and measured.

Ten additional sites were chosen to measure runoff from 1-m^2 plots subjected to simulated rainfall from a rotating-disc rainfall simulator (Morin and Cluff, 1980). Five of the plots had undisturbed BSC covers; the other five plots had been plowed by LTERS foresters to control weeds and thus had no crust. Each runoff plot was constructed from four sheets of steel hammered into the soil to a depth of about 5 cm. A sloping flume was connected to each plot at the downhill edge to collect runoff water. The flumes and collecting device were covered from above to prevent raindrops from entering as they collected runoff. A flexible hose attached to a vacuum pump was connected to the lower end of the flume, by which runoff from the flume was pumped into a graduated cylinder to measure the volume of water collected at 1 min intervals from the moment water ponding commenced until a steady-state runoff rate was achieved. The rainfall simulator nozzle delivered simulated raindrops from a standard height of 2.05 m, producing rainfall of 2.5-mm diameter mean drop size with energy of approximately 30 kJ m^{-2} min^{-1} at a pressure of 60 k Pa. Although rainfall intensity was set at 37.5 mm h^{-1}, measured intensity (mean = 47.2 mm h^{-1}) varied slightly among plots according to height above the ground (Eldridge, Zaady and Shachak, 2002). Distilled water was used for rainfall simulations to avoid any influence of cations. Intensity was calibrated by collecting all of the rainfall at the commencement and cessation of simulations each day. Simulated rainfall was applied at a constant rate for 30 minutes, which was sufficient to achieve steady-state runoff.

The source of the biogenic soil crusts and soil samples, and the location of the field experiments, was—as stated above—the north-facing slopes of the watershed.

Statistical Analyses

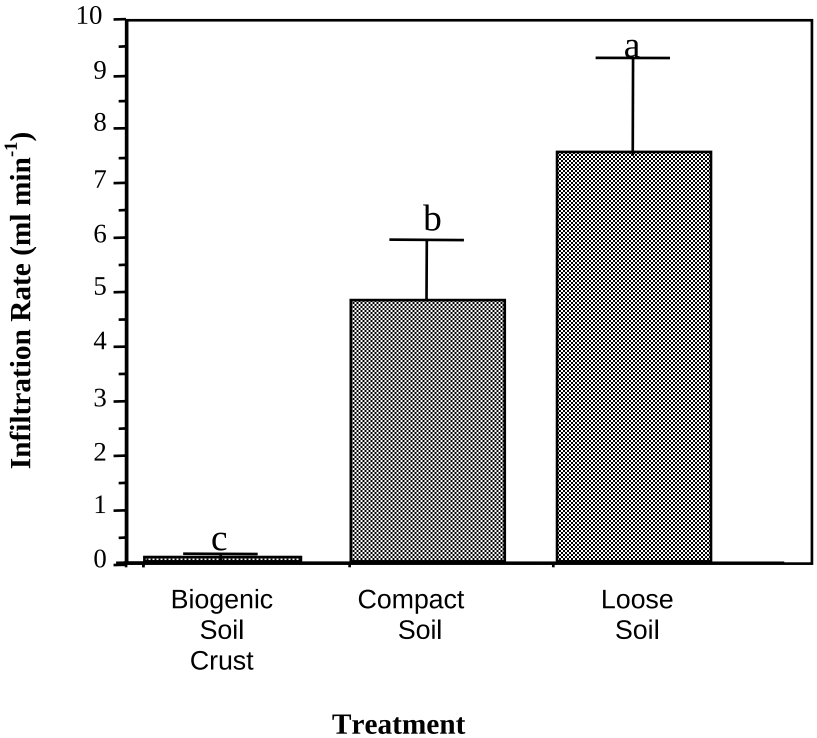
One-way ANOVA, with Duncan New Multiple Range (Sokal and Rohlf, 1995), were used to test differences in infiltration and runoff among crust types for all three studies. Results are expressed in the text as mean ± standard error of the mean (S. E. M.).

Results

Small-scale laboratory studies

With the small-scale study, infiltration was lowest in the Petrie dishes containing BSC and highest in loose soil ($P<0.001$; Figure 14.1). The infiltration rate in the loose soil was about 30 times greater than that in the controls (Figure 14.1). Water began seeping through the base of the Petrie dishes with loose soil about 2–3 minutes after addition of water compared to 28 minutes on the dishes with the BSC. Most of the water that did infiltrate though the crust did so along the edges of the crust samples or via the narrow seams between individual crust platelets.

Figure 14.1. Infiltration rates for three different crust types in a laboratory experiment; biogenic soil crust as compared to physico-chemical (compact) crusts and loose soil as controls. Different letters indicate a significant difference in that variable at P<0.05. Bar represents S.E.M.



Field and simulator studies

Although runoff was produced in each of the five years, not all rainfall events result in runoff. Small, scattered storms of intensities less than 5 mm h^{-1} produced no runoff due to the low moisture content of the soils and the fact that the interception capacity of the soil surface was not exceeded. Over the five years of measurements, 19–32% of the rainfall was lost as runoff. For rainfall events that produced runoff, increasing annual rainfall was associated with increasing runoff ($F_{1,4}$ = 38.44, P=0.003, R^2=0.882; Eldridge et al., 2002).

With the rainfall simulation study, BSC disturbance significantly affected runoff rates (P=0.027). Runoff from the five biogenically crusted plots was significantly greater than from the plowed plots (Table 14.2), and the increase in runoff rate from the control plots (mean = 1.5 mm h^{-1} min^{-1}) was three times greater than from the other treatments (0.5 mm h^{-1} min^{-1}). Approximately one-third of all applied water was lost as runoff on the natural BSC plots, whereas the plowed plots lost less than 15% of applied rainfall as runoff (Eldridge et al., 2002).

Discussion

These studies, at spatial scales varying from centimeters to meters, provide supporting evidence that BSC communities in the northern Negev Desert enhance runoff production (Table 14.2). At both scales, infiltration was retarded by the presence of BSC, which, when disturbed in the field experiments, resulted in enhanced infiltration.

Redistribution of water is crucial for the sustained functioning of landscapes in the Negev Desert. Our laboratory study showed that despite low hydraulic conductivity (Eldridge et al., 2000), BSC did allow some infiltration of rainfall into the soil crust. This is supported by our studies at the broader sub-landscape scales, where 19–32% of the rainfall (or applied simulated water) was shed as runoff (Eldridge et al., 2002).

Table 14.2. Mean runoff production after rainfall simulation on plots with biogenic crusts and on plots where crusts have been removed by plowing

Soil surface type	Runoff water (mm hr^{-1})[a]
Biogenic soil crust (n=5)	13.7 a
Plowed (n=5)	4.1 b

[a]Means with the different letters within a column indicate a significant difference in that variable at P<0.05.

The runoff coefficients recorded in the rainfall simulation study were almost double those recorded from the small plots at the LTERS under natural rainfall conditions (Eldridge et al., 2002; Zaady et al., 2004). The reason for this lies partly in the characteristics of natural rainfall (rainfall discontinuity), which are often poorly reproduced by rainfall simulators, and partly in the discontinuous spatial distribution of water ponding. Natural rainfall is highly intermittent (Kidron and Yair, 1997), with short-duration high-intensity storms often less than a few minutes in duration. Typically, these are separated by rain-free periods of many minutes (Kidron and Yair, 1997), or by longer intervals where the intensity is lower than the hydraulic conductivity of the substrate. This rain-free period may even be sufficient to allow the sediments to drain and dry. The result is that the pattern of water ponding is unlikely to be contiguous across a plot. Under natural rainfall, zones of water ponding will develop (Dunne, Zhang and Aubry, 1991), separated from other zones of high hydraulic conductivity that often do not normally pond because of abundant plant roots or faunal macropores (Beven and Germann, 1982). Consequently, during natural rainfall, only small, spatially noncontiguous areas of the surface may pond. Depending on the arrangement of these ponds, runoff will often be short-lasting and intermittent. The duration of water ponding and runoff is often less than the concentration time required for continuous flow along an entire slope – or from the top of a mini-catchment to the flume. In contrast, rainfall simulators deliver constant rainfall intensity with little or no temporal variability. Under simulation, water ponds rapidly, often spreading out onto areas which would not normally pond water under natural conditions. The result is greater runoff and therefore a higher runoff coefficient than would otherwise occur under natural conditions.

Reduced infiltration through the crust at the LTERS resulted from a combination of the high water-shedding capability of the crusts, surface sealing by biogenic elements at the surface, little or no surface obstruction by plants, an enhanced surface roughness created by the crusts themselves, and relatively long slopes. Our results showed a significant decrease in runoff water generation from heavily disturbed (plowed) plots as compared to natural undisturbed BSC plots (Table 14.2). This is supported by other studies in the Negev Desert using disc permeameters (infiltrometers) which showed that removal of the crust enhanced infiltration under water-ponding conditions but not necessarily under tension (Eldridge et al., 2000).

What then is the mechanism whereby BSC reduce infiltration and increase runoff? Cyanobacteria are widespread in the surface soils of the Negev Desert and at the LTERS they comprise a tightly structured surface community (Zaady et al., 2000). The two dominant cyanobacteria at this station are *Microcoleus vaginatus* (Chroococcales) a filamentous cyanobacterium that grows 1–2 mm below the soil surface and moves to maintain this depth, and *Nostoc punctiforme* (Oscillatoriales), a species that grows on the soil surface (Lange et al., 1992). These two species are known for their ability to secrete mucilaginous polysaccharide sheathes, which bind micro-aggregates (<0.25 mm in diameter) at the surface to produce macro-aggregates (Bailey et al., 1973; Belnap and Gardner, 1993; Moore, 1998). Matrix pores close to the soil surface often become colonized by cyanobacteria, typically creating a hydrophobic surface and reducing further water absorption (Rostango, 1989). Other less common cyanobacteria in the crust include *Chroococcus tugidus*, *Calothrix* sp. (Oscillatoriales) and the green algae *Palmella* sp. (Tetrasporales) (Metting, 1981; Zaady et al., 2000).

The development of a stable, hydrophobic crust is often dependent on other biogenic elements, such as mosses, to provide a structure upon which the cyanobacterial filaments can attach (West, 1990). The two most common mosses in the area are *Aloina bifrons* (Pottiaceae) and *Crossidium crossinerve* var. *laevipillum* (Pottiaceae), both of which are adapted to arid climates (Scott, 1982). Other mosses, such as *Bryum* spp. (Bryaceae), which colonize sheltered sites in the lower parts of the watershed, represent a higher successional stage in the development of a BSC (Zaady et al., 2000).

By generating runoff, BSC in a fully functional state controls the flow of resources (e.g., sediments, nutrients and seeds) across the landscape (Shachak et al., 1998). The northern Negev landscape is a mosaic of patches of BSC and shrubs. The arrangement of the landscape mosaic in a natural state is such that resources generated by the BSC patch are captured by and accumulate in the shrub patch. While the crust patches are sources for soil, nutrients and runoff water (Rostango, 1989; Eldridge, 1993; Abrahams, Parsons and Wainwright, 1994), shrub patches are resource sinks and the major loci of productivity and diversity. This is mainly due the accumulation of sediments, nutrients and water under the shrubs, which promotes a rich growth of associated herbaceous vegetation (Noy-Meir, 1985; Garner and Steinberger, 1989; West, 1989; Schlesinger et al., 1990; Zaady et al., 1996). The natural source-sink relationship between the two patch types is critical to the functioning of the ecosystem. Human activities (e.g., clear-cutting of shrubs for firewood, livestock grazing on shrubs) reduce the abundance of shrubs and disturb this relationship (Bruins, 1990; Ludwig and Tongway, 1995; Ludwig et al., 1997). Location of the ecological system along the precipitation gradient determines the relationship between the crust and shrub patches; therefore, there is an inverse relationship between annual precipitation and crust-to-shrub cover ratio (Zaady et al., 1997). Reduction in shrub cover leads to an increase in crust cover and vice versa. When resources shed from the crust patches are not sufficient to support the shrub patches, landscape diversity and productivity decrease. Heavy grazing or clear-cutting of shrubs increases crust cover, leading to leakage of resources from the system, followed by reduced productivity and diversity (Graetz, 1991; Thomas, 1995). To maintain the highest possible productivity and diversity in this system a balanced ratio of the two patch types must be maintained. Any change in the landscape mosaic, in either direction, promotes desertification processes.

Applications for increasing productivity in dry landscapes

Based on long-term ecological research, the Forest Department of the Jewish National Fund (JNF) in Israel uses contour catchments as a management practice in the forest-parks of the northern Negev to create sink patches on the slopes (Shachak et al., 1998). The contour catchments are strips of soil mounds 1 m high, constructed parallel to each other along the contour lines of the slopes. The distances between the contour catchments are 15–25 m. Their role is to trap and collect surface runoff water that leaks from the undisturbed natural areas of BSC and dwarf shrubs between the catchments. Soil for construction of these catchment mounds is scraped from a 1-m wide strip of surface soil immediately below the catchments and then piled up to form a mound. The crusted soil surface 1–2 m immediately above the mound is plowed to increase water infiltration for the trees, which are planted upslope of the mound. The trees are planted 7 m apart. Each tree exploits the rainfall it receives directly along with the runoff water it receives from the crusted area above it (Zaady, Shachak and Moshe, 2001).

In our study area, the average rainfall per year is 200 mm. Runoff water 1 mm in depth from a 1-m^2 catchment area amounts to 1 liter. The average shading area under the tree canopy, in this area, is 3×3 m. The amount of rain that falls directly on this tree is thus 200 liters $m^{-2} \times 9\ m^2 = 1{,}800$ liters. On average, 19–32% of the natural annual rainfall (and 25.5% of the applied simulated rainfall) was shed as runoff (Eldridge et al., 2002). The trees are planted 7 m apart, so a BSC-contributing area between two contour catchments 20 m apart and two trees 7 m apart is $7\ m \times 20\ m = 140\ m^2$. Therefore, $0.255 \times 200\ mm \times 140\ m^2 =$ 7,140 liters of water, which can be collected by this arrangement (Zaady et al., 2001). This amounts to 5,340 liters of additional runoff water for each tree.

Our results from this study showed that with proper ecological management of the landscape and its resources, afforestation is possible in dryland areas. The presence and the attributes of BSC cover can be utilized to enhance productivity, diversity and sustainability of desertified landscapes the world over**.**

Acknowledgements

We thank the Jewish National Fund; the Blaustein International Center for Scientific Cooperation for supporting the visit of one of the authors (DJE) to Sde Boker to undertake the research; the New South Wales, Australia Department of Land and Water Conservation for supporting the research; R. Garti and Y. Benyamini from the Soil Erosion Research Station, Israel Ministry of Agriculture for use of their portable rainfall simulator; E. Fizik and R. Levcov for assisting with the field experiment, and S. Brand and A. Leeper for commenting on and editing the manuscript.

Applicative methods for aeolian particle study in desert environments[1]

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Wind may be considered the most dynamic of the agents that affect the surface of semi-arid and arid areas of the earth. Wind acts with variable intensities but without interruption all year long. It transports material resulting from soil erosion, weathering and disintegration, over short, medium or long distances, causing significant loss of soil in many areas, often causing considerable discomfort to local populations, finally settling down to form either uniform deposits (sand sheets, dust sheets) or very distinctive topographic relief forms (dunes, dust knolls). Wind may also sort the transported materials and deposit them accordingly.

Aeolian particles are a major constituent of the earth's atmosphere, especially in arid and semi-arid regions. They affect many aspects of daily life, including the economic development of these regions. Most aspects of human activity in desert regions and neighboring areas are affected by such particles, including agriculture, transport (by road and by air), solar energy and construction (in rural, urban or industrial settlements). Therefore, during the past 20 years, aeolian dust has become a major topic in environmental studies. The sources, entrainment, aerial transport and deposition of dust are of great importance to human activity and health (Rheis and Kihl, 1995) and to environmental evolution and development (Goudie and Middleton, 1992) in arid and semi-arid areas. Aeolian dust also plays a role in the development of soil, both as a controller of chemical pedogenic processes and as a supplier of mineral and biotic particles; it also improves the soil moisture regime.

Several studies focusing on the problems and implications of atmospheric dust have been published. They include a wide variety of subjects, e.g., the relationship between weather type and dust storm generation, synoptic conditions during dust events, local and intercontinental transport of dust, dust occurrence and climatic variation, reports of dust events in several parts of the world, current dust deposition compared with the past, the mechanisms of dust erosion, dust transport and dust deposition.

Large amounts of dust are usually found in the atmosphere above or near deserts. The quantity depends on many factors, including location, size and lithology of the source, regional and local meteorological circumstances, distance from the source, and general and local topographical location. These large amounts of dust may have an important impact upon the local weather or atmospheric circulation in the desert boundary layer. Since the fringe areas of many deserts and semi-deserts are expanding rapidly, atmospheric particles are one of the major natural components that should be studied to improve the economic potential of these areas. In deserts and adjacent regions affected by low rainfall, silt and clay-sized particles are propelled from different sources. These include alluvial deposits on dry flood plains, wadis, playas, loess-rich hamadas, alluvial fans, etc. Reduced fertility of systems is one of the most definitive and problematic aspects of desertification (Dregne, 1986; UNEP, 1991).

In the Negev Desert, several aspects of aeolian dust have been studied by Offer and Goossens (2001a), particularly, the relationships between aeolian dust and meteorological parameters. Offer and Goossens (2001b) investigated the effects of desert topography on aeolian dust erosion, deposition and accumulation. Esser (1989) studied the role of aeolian dust deposition in a desert ecosystem. A general study of the relationships between dust, soils and landforms in the deserts of southern Israel and the Sinai was published by Gerson, Amit and Grossman (1985).

The following deals with field methods we used to study aeolian dust dynamics and to analyze particle size distribution, micromorphology and chemistry of dust in the Negev desert at the Avdat Experimental Station, near Sde-Boker. These methods are applicable to similar environments worldwide.

Comparisons among four aeolian dust collectors

Four different dust-collection methods were tested at the Avdat Experimental Station (Goossens and Offer, 1994). Each method in the Avdat experiment employed four plastic sedimentation trays installed in the field. These trays were circular (to eliminate the effects of wind direction change), 10 cm high, and 30 cm in diameter. Each collector contained a different sedimentation surface. Surface No. 1 was dry and flat (an empty collector tray). Surface No. 2 was dry and contoured, consisting of two superimposed layers of marbles (marble diameter: 1.6 cm). Surface No. 3 was flat and moist, consisting of filter paper fastened onto a wet sponge. Surface No. 4 was a free water surface (a collector filled with a 1 g liter^{-1} $CuCl_2$ solution to prevent algal growth). Surfaces No. 2, 3 and 4 were about 5 cm below the rim of the tray, whereas surface No. 1 was 10 cm below the rim at the bottom of the tray itself.

Collectors were in operation at the respective locations for a period of 24 months. Each month, the total amount of dust accumulated on the surfaces was measured, and new, fresh collectors were installed. Dust that had accumulated on surfaces No. 1 and 2 was collected with a brush, whereas dust that had accumulated on surfaces No. 3 and 4 was directly determined by weighing the sediment after the water had been evaporated in an oven.

Table 14.3 shows the total amount of dust accumulated on each collector during the Avdat experiment. The results were parallel for all months: the water surface always collected the largest quantity of dust, followed in order by the marble surface, the moist filter paper surface and the dry flat surface. The first year, dust accumulation on the dry flat surface was only 40% of the amount collected on the water-filled collector, while the moist filter paper collector and the

Table 14.3. Dust accumulation (g m^{-2}) on dust collector types at Avdat, and collector efficiency (percent, in italics) relative to the water collector, averaged over two years

	Dust accumulation each month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Whole Year
Dry flat surface	4.4	7.2	7.5	6.5	8.5	9.4	5.5	4.7	6.2	8.3	7.8	6.9	82.7
	41%	*50%*	*44%*	*40%*	*47%*	*52%*	*39%*	*37%*	*44%*	*52%*	*45%*	*45%*	*45%*
Flat moist filter	5.3	8.1	8.6	8.6	11.3	12.2	8.7	6.8	8.4	10.0	10.0	8.2	100.9
	50%	*57%*	*51%*	*52%*	*62%*	*67%*	*61%*	*53%*	*59%*	*63%*	*58%*	*53%*	*55%*
Glass marbles	7.9	12.0	11.7	10.9	13.9	14.2	9.5	8.0	10.4	13.3	14.6	12.2	138.3
	74%	*84%*	*69%*	*67%*	*76%*	*78%*	*70%*	*63%*	*73%*	*83%*	*84%*	*79%*	*75%*
Water	10.7	14.3	16.9	16.4	18.2	18.2	14.2	12.8	14.2	16.0	17.3	15.4	184.3

marble collector collected 49% and 71%, respectively. The second year, the relative order remained the same, but the relative percentages were somewhat different: 49%, 60% and 79%, respectively. Meteorological conditions, especially wind velocity, show an important variation with time (Goossens and Offer 1994). Furthermore, accumulation is largely determined by aeolian erosion, which is greatly dependent upon the frequency and intensity of the strongest winds.

Temporal variations in relative accumulation efficiency of the collectors were small over the 24-month period. No systematic trend was observed for any of the four collectors, and the differences within each collector remained small (a few % at maximum), except for the water collector, where some variation was observed during the first year.

Optimal measurement for aeolian dust deposition

Various experimental setups to measure dust deposition have been reported in the literature, including simple setups (Skärby, 1977) and complex setups: e.g., buckets (Köhler and Fleck, 1963), vertical gauges (Ralph and Barrett, 1976), filters under cover (Pattenden, 1977 cited in Steen, 1979) and moss-bags (Goodman et al., 1979). The efficiency of these methods, however, remains questionable. An optimal gross-deposition measuring method should both include free, undisturbed sedimentation on a surface, and a total prevention of redeflation of the settled sediment.

One of the four methods used in the Avdat experiment described above may be characterized as a 'permanently moist surface method'. The flat plastic tray was partly filled with clean water and a thin, fully wetted sponge was placed on the water surface. Due to its weight, the sponge sank into the water until its upper surface was nearly at the same level as the free water surface. The tray was then further filled with water until the sponge surface reached its maximum level. A filter paper (stabilized with inoxidable pins) was then placed on the sponge surface. It was immediately wetted by the water in the sponge. As dust particles settled on the filter paper, they were retained, due to the strong capillary forces of the water (Goossens and Offer, 1990).

The great advantage of this method was that the dust-collecting surface remained permanently moist, even if a very thick layer of dust formed on the filter paper. Due to capillary forces (which can reach very high values in fine-grained sediments such as desert dust) the top layer of the settled dust remained moist as long as water was available in the tray. Even under extremely hot desert conditions (with enormous evaporation rates) the collecting surface remained moist during prolonged periods of time, especially if the shape of the sponge matches the shape of the top of the tray (effectively preventing exposure of free water to the sun). The collecting surfaces remained moist the during the entire Avdat experiment (24 h), despite temperatures of up to 29°C and a water storage content of only 10 liters (Goossens and Offer, 1990). The filter paper used at Avdat was 28 × 32 cm, corresponding to an area of 0·0896 m^2. A plastic sheet on the ground prevented erosion of the soil in the immediate vicinity of the measuring site.

The efficiency of the method is dependent upon the position of the tray on the ground. If the tray is not dug into the ground, air-flow patterns will be disturbed by the tray itself, resulting in a lower catching efficiency. A dug-in tray may, however, also catch material that has been supplied by saltation or surface rolling, and not only by suspension. To avoid saltation, it is advisable that a tray be used that is high enough to exclude saltated particles. The efficiency of the set-up should also be determined experimentally (i.e., in a wind tunnel). Tray efficiency is influenced by the size and shape of the tray and by its orientation with respect to wind direction; circular trays would be ideal. Efficiency is also dependent upon air velocity itself: high air velocity lowers efficiency, relative to low air velocity. Fortunately, most of these influences disappear when the tray is completely (but carefully) dug into the ground.

Aeolian dust erosion

Various techniques are used to measure aeolian dust erosion in the field. Most of these methods refer to erosion of sandy surfaces or agricultural soil. Examples are the use of erosion pins (Jungerious and Van der Meulen, 1989; Pluis, 1992) or tracers (Plasschaert, 1985). Other techniques are based upon topographic measurements (to determine the volume of the sediment eroded) or upon mass analysis of standard plots (Offer and Goossens, 1994).

At the Avdat Experimental Station a cardboard plate, 0.8 × 0.5 m in size and 4 mm thick, was installed on thirty 1.0 × 1.0 m plots from which the largest rock fragments had been removed (their removal facilitated placement of the cardboard plates flush with the surface to keep the wind from blowing underneath them, which would have seriously disturbed the erosion measurements). An erosion area 0.5 m × 0.5 m was marked off in the middle of each cardboard plate. These erosion squares were covered with exactly 1 kg of dust, prepared from loess that had been collected just north of Avdat and sieved in the laboratory to exclude all particles >60 μm. All the squares received the same quantity of dust, regardless of their topographic position. The inclination of all the cardboard plates was equal to that of their underlying slopes. Cardboard plates were affixed to the natural surface with metal pins. Before and after the experiment, they were covered with a 1 × 1 m plastic sheet to prevent unwanted deflation (Offer and Goossens, 1994). Erosion was calculated by determining the quantity of dust that remained on the erosion surface after the experiment. The measurements were made with a precision of 0.0001 g.

From the description above, it follows that all the erosion surfaces were smooth. This was done for two reasons. Firstly, and most importantly, it allowed us to install erosion surfaces of equal surface roughness. The effect of microroughness upon aeolian dust erosion is therefore eliminated; thus, the field experiment reflected only the effect of macro-roughness (i.e., topography). (This was also the aim of the wind tunnel simulations, as mentioned earlier). One should also realize that the effect of micro-roughness upon aeolian dust erosion is almost impossible to simulate on topographic scale models, simply because of the large reduction of scale. Moreover, micro-roughness in the wide surroundings of each plot at Avdat was almost identical: all the plots were located on stony or rocky surfaces of equal roughness. A small square 0.8×0.5 m within this rocky area would not significantly influence the general roughness of the field.

Methods for particle size distribution, micromorphology and chemistry

Our aim was to try a new approach to investigate aeolian particle granulometry and micromorphology in a sandy-loessial area. We used such parameters as: total aeolian deposition, particle perimeter (P), particle area (A), long (L_1) and short (L_2) particle axes, particle roughness ($R_1 = 4\pi A/P^2$) and particle sphericity ($R_2 = L_1/L_2$). These parameters were analyzed on spatial and temporal scales.

The size distribution of the particles on the filters was analyzed with a computerized scanning electron microscope (SEM), which facilitated investigation of the micromorphological and chemical characteristics of the particles (Figure 14.2A, B, C, and D).

Our estimation of the particle size distribution was based on a planar projection of the particles. The value of the particle area (in μm^2), was defined as the surface of the particle enclosed within the projected border, i.e., the perimeter, (in μm). This must be compared to the classic size parameter, i.e., the diameter of the smallest circle enclosing the whole plane projection of the particle (Alshibli et al., 2004).

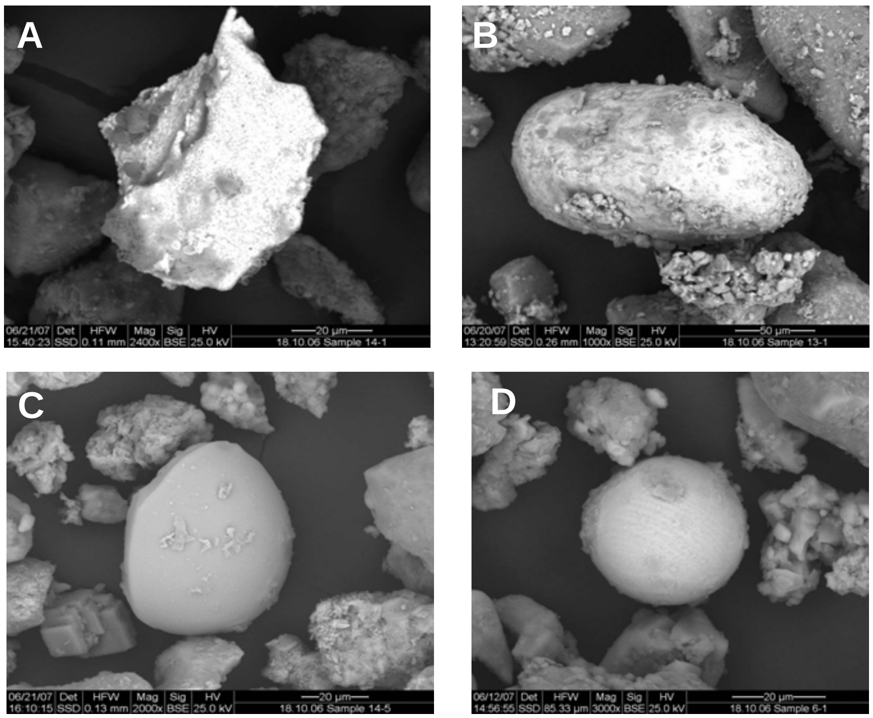
Using an SEM instrument (type JSM 5410 JEOL), a series of parameters were measured on a large number of particles: the projected surface area (A, in μm^2), the projected perimeter (P in μm) and the projected long (L_1) and short (L_2) axes (in μm). From these values two dimensionless ratios (projected particle roughness R_1 and projected particle sphericity R_2) were computed for a large number of particles.

The first parameter, R_1, was defined as $R_1 = 4\pi A/P^2$. This parameter characterizes the irregularity of the contour of the particle, i.e., the roughness of the particle surface, as compared to the smoothness of a perfectly spherical surface (Alshibli et al., 2004; Donat and Ruck, 2004; Vanderstraeten et al., 2006a, 2006b).

The second parameter, R_2, refers to the elongation of the particle and corresponds to the ratio of the projected major axis, L_1, divided by the minor axis, L_2, of the smallest ellipse enclosing the planar projection of the particle.

The interest in introducing R_1 and R_2 comes from the fact that they are largely uncorrelated parameters. In other words, there is no obvious correlation between the elongation and the roughness of the particles and, therefore, these parameters provide independent and complementary information on the morphology of the particles.

Figure 14.2. SEM (Scanning Electron Microscope) photographs of aeolian particles (see Table 14.4 for size distribution, micromorphology and chemistry details for each particle)



To determine the value of the projected area (as particle size) and the form of the particles (especially the very small ones), the particles were analyzed at various resolutions (magnitudes). The micromorphology of the airborne particles was analyzed by computerized SEM investigation with a Soft Imaging System (SIS) (digital solutions for imaging and microscopy). From the data obtained by the SEM, the values for R_1 and R_2 could then be calculated (Table 14.4). The chemical compositions of the particles, also gained from the SEM, are given as percent of the total weight of the elements presented (Table 14.4).

Among the four types of dust collectors tested—wet-flat (water), dry-contoured (marbles), dry-flat and moist-flat—the water collector received the greatest quantity of both deposited and accumulated sediment. Deposition on the marble collector is comparable to that on the water collector, but as the former is more sensitive to post-depositional erosion, accumulation on it is markedly lower. The effect of post-depositional erosion is even more clearly observable in the case of the other collector types tested: in general, deposition was lower on the moist-flat collector than on the dry-flat collector, but because the latter is extremely sensitive to erosion, accumulation on it was always smaller (Goossens and Offer, 1994).

The type of collector used in a particular situation depends largely on the aim of the measurements. If, for example, the chemical composition of the sediment deposited is to be determined, no water (or moisture) collectors can be used because the water will react with the sediment. If, on the other hand, the total amount of sedimentation (or accumulation) is of primary concern, water will give the best results, provided algal development and insect penetration can be kept to a minimum. Careful consideration of the sampling method should, therefore, be made in advance (Goossens and Offer, 1994). Only four types were tested in this study. Many other types can be used and future research is necessary to test them. At present, we consider the use of marble collectors to be most convenient, because of their simplicity, handiness and lack of maintenance, and we propose that this type should be used as a standard in future dust deposition (or accumulation) research (Goossens and Offer, 1994).

Table 14.4. SEM (Scanning Electron Microscope) analyses of the aeolian particle size distribution micromorphology and chemistry (see Figure 14.2)

Sample	**Area**	**Perimeter**	**Area/ Perimeter**	**Long Distance**	**Short Distance**	**Long/ Short**
	μm²	μm		μm	μm	
A	2871.48	250.07	11.48	66.42	57.53	1.15
B	16656.63	512.50	32.50	188.81	106.78	1.77
C	2709.16	201.37	13.45	67.93	50.25	1.35
D	934.82	108.38	8.63	34.43	34.43	1.00

Sample A		**Sample B**		**Sample C**		**Sample D**	
Element	%	Element	%	Element	%	Element	%
O	22.67	O	44.29	O	43.49	O	23.93
Si	5.01		29.11	Si	3.15	Si	3.74
Sn	19.75	Zr	26.59	S	3.80	Fe	72.33
Zn	14.63			Cl	5.91		
Pb	37.94			Ca	1.11		
				Cr	11.09		
				Fe	31.46		
Total	100.00	Total	100.00	Total	100.00	Total	100.00

Concerning **dust deposition**, the results of the Avdat experiment demonstrate that it is possible to simulate actual dust deposition in a particular area with a topographic scale-model experiment (Goossens and Offer, 1994). Secondly, the Avdat experiment demonstrates the order of magnitude of the gross sedimentation of atmospheric dust during a moderately to very dusty day in the northern Negev desert. Sedimentation is strongly influenced by topographic location (Goossens and Offer, 1988). And finally, the Avdat data can be used to calculate the deposition velocity of Avdat dust during a moderately to very dusty wind storm. The deposition velocity, an important parameter in theoretical dust deposition models, is usually noted as v_d and is defined by the following equation:

$$v_d = F/C \qquad (1)$$

where F is the downward sediment flux and C the airborne sediment concentration. The reference height for C is usually 1–1.5 m for land surfaces, and 10–15 m for ocean surfaces. Particle deposition velocity is greater than or equal to gravitational settling velocity (v_t), which increases proportionally with particle density and the square of particle diameter (Goossens and Offer, 1990).

As for **dust erosion**, the wind tunnel and the field results show reasonable agreement. In a previous paper (Offer and Goossens, 1994), wind tunnel simulations of aeolian dust deposition on the same Avdat scale model were compared with field deposition data obtained during a full-scale dust storm. These simulations showed a 90% agreement with the field deposition data. However, wind tunnel simulations of aeolian dust deposition are conceptually different from wind tunnel simulations of aeolian dust erosion: local surface parameters (e.g., surface roughness) have a very strong impact on the erosion process.

The general sedimentation pattern of dust deposition is largely determined by the global airflow pattern over the region, which depends primarily on macro-topography. Thus, accurate simulations of aeolian **dust deposition** require a correct simulation of the general airflow field over the scale model, while a correct simulation of aeolian **dust erosion** at any particular point on the model also requires a correct simulation of surface roughness at that point. As the latter is much more difficult to realize, erosion simulations on topographic scale models can be expected to be less accurate than deposition simulations (Offer and Goossens, 1994). The Avdat experiment shows that wind-tunnel simulations of aeolian dust erosion on scale-models of a complex topography may reasonably predict the location of erosion-sensitive areas in a hilly landscape of nearly uniform surface roughness. When surface roughness is nearly uniform, aeolian erosion of (dry) dusty sediments is almost entirely determined by macro-topography, as was illustrated by the Avdat experiment (Offer and Goossens, 1994).

As for particle size distribution, micromorphology and chemistry, the difference between the specific soil-particle size-distribution for a given location and the aeolian material deposited in the collectors at that location might be explained by tropospheric wind activity and its interaction with the soil surface. The specific form of the collectors induced turbulent air movement and decreased the possibility of deflation of the relatively larger particles.

In our estimation, one of the most important parameters for understanding the characteristics of aeolian particle micromorphology and atmospheric particle dynamics is **particle area**. We analyzed this parameter from two different aspects – spatial and temporal. The size differential may be explained by terrain morphology and by the overland water runoff that easily transports smaller particles downstream.

The *R1* micromorphological parameter ($4\pi A/P^2$) describes the roughness of the particles. Particles with the same projected area may have perimeter lengths (hence shapes) that are very different.

The soil surface may be covered with annual vegetation during specific seasons that might decrease wind velocity close to the ground. This may affect the particle configuration, far from the spheric shape, as a result of decrease in wind erosion, which causes shortening of their time-movement in the atmosphere.

The classic method for determining particle size (Alshibli et al., 2004) does not facilitate investigation of particle roughness (R_1) or sphericity (R_2). Our method offers possible advantages in human-health fields by providing more detailed information on size distribution and shape (roughness and sphericity) of the particles that affect respiratory processes. This method also offers advantages in the field of mechanical engineering, providing greater understanding of the influences of airborne particles on turbines, motors, glasses and filters in corrosive processes. Furthermore, this method may contribute to the meteorological study of cloud formation by offering a greater understanding of how particle size distribution and shape affect condensation mechanisms and ice nuclei formation.

Atmospheric particle dynamics are a direct result of wind activity and ground surface features. Our comprehensive approach better facilitates detailed calculation of particle size distribution and particle roughness and sphericity for these purposes.

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