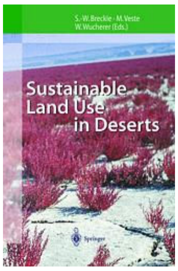

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The Role of Biological Soil Crusts on Desert Sand Dunes in the Northwestern Negev, Israel

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Keywords. Biological crusts, soil lichens, sand stabilization, combating desertification

Abstract. Biological soil crusts are important microphytic communities and significantly influence both structure and processes within the ecosystem. They are built up from cyanobacteria, green algae, fungi, mosses and lichens. Various crust types could be found, depending on dune slope aspect and dewfall availability. In the sand dunes of the northern Negev they cover large areas and stabilize the sand surface against wind and water erosion. Free-living and symbiontic cyanobacteria are capable of nitrogen fixation and are important nitrogen sources in the desert sand dunes. As biological crusts enhance the surface stability and soil fertilization, they are to be considered a key factor in the protection of arid and semiarid ecosystems and, thus, in combating desertification in terms of sand dune remobilization.

Introduction

Shifting sands are one of the major problems of desertification and land degradation in arid and semiarid areas. Nearly 20% of the world´s arid zones are covered by aeolian sand (Pye and Tsoar 1990). Such fragile ecosystems are very sensitive to land use practices. Grazing and trampling by livestock and agricultural use destroy the vegetation cover and enhance sand mobility, thus accelerating desertification processes. In most arid regions of the world, sand dune movement is a threat to irrigated farmlands, villages, railways, highways and other infrastructures. In the deserts of the Middle East, sand dunes in Egypt cover 16% of the area (Misak and Draz 1997), 21% in the Sinai and 13% of the Negev (Danin 1996). The sand dunes of the northwestern Negev are the eastern extension of the northern Sinai sandfield (Veste 1995, Veste and Breckle 2000) and are characterized by linear forms in the southern part and complex dunes in the northern part.

The sand dune field has been inhabited by Bedouin nomads, who use the interdunes for crop growing, while goats, camels and donkeys graze the dunes

(Tsoar and Møller 1986). The intensive grazing led to a decrease in the vegetation cover on Egyptians territory (Tsoar et al. 1995), whereas on the Israeli side, the vegetation remained undisturbed from 1948 to 1967 and again since 1982. The differences could be observed in satellite images (Otterman and Waisel 1974, Danin 1996). The higher surface wind speed in combination with a high relief energy results in increased sand mobility. In 1967, the border between the Negev and the Sinai was opened, and the vegetation on the Israeli side was severely overgrazed (Tsoar et al. 1995). After the reestablishment of the borderline and land use changes in 1982, the vegetation recovered on the degraded Negev areas. Along with vegetation recovery, a thin biological soil crust established itself on the sand dunes. The structure of these biological soil crusts and their function for the ecosystem processes were investigated in the linear dunes near Nizzana and along the geoecological gradient (Fig. 1).

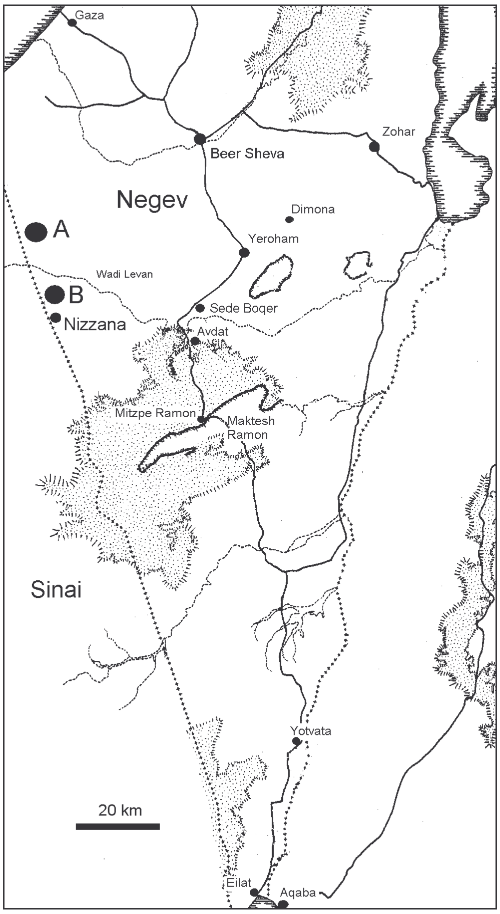

Fig. 1. Map of the Negev desert and location of the investigation sites. *A* Halzua sand field, average annual rainfall 120 mm; *B* Nizzana, average annual rainfall 90 mm.

Biological Crusts

Biological soil crusts are common cryptogamic communities in various arid and semiarid regions. They are reported, for example from Australia (Eldrige and Greene 1994), North America (West 1990; Johansen 1993), from the sand dunes of the South African Succulent Karoo (M. Veste, pers. observ.) and from various habitats of the Negev desert in Israel. The sand dunes of the northwestern Negev are covered over wide areas by crusts. The biological crusts are built up by soil material and by cyanobacteria, green algae, mosses, fungi and soil lichens. Most of the crust flora of the sand dunes near Nizzana are cyanobacteria and are represented by *Microcoleus sociatus*, *Calotrix perietina* and *Nostoc* sp.; the Chlorophytes are represented by *Chlorococcum* and *Stichococcus* (Lange et al. 1992). Most of the organisms inside microphytic crusts are still unidentified. In the Negev sand dunes various crust types could be distinguished following crust thickness, chlorophyll a content, and colour in the sand dunes near Nizzana (Fig. 2). Light brown crusts with an average thickness of 1–3 mm occur in the interdune and on south-facing slopes, whereas the crusts on north-facing slopes are darker. Here, the chlorophyll a content may serve as a measure for crustal biomass and the crust thickness. Mosses (*Bryum* spp.) are common on the north-facing slopes and especially at the dune base (Fig. 2). Soil lichens occur in the interdune area and on stable and flat north- and northwest facing slopes in the northern Haluza sand field (Fig. 1) and cover here up to 90% of the area. Cyanobacterial lichens like *Collema* spp. dominate the soil crusts. The green-algae lichens *Fulgensia fulgens, Squamarina cartilaginea, Squamarina lentigera* and *Diploschistes diacapsis* were observed locally on small soil mounds.

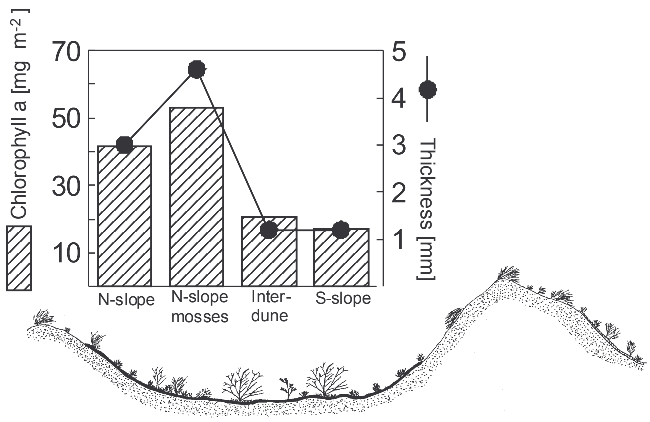

Fig. 2. Chlorophyll content and thickness of the biological crust in different geomorphological units in the sand dunes of Nizzana

Dew Fall and Crust Activity

The development of the biological crusts seems to be determined by two main environmental factors: (1) sand stability and (2) the microclimatic boundary conditions, especially the moisture regime (Veste et al. 2000). Dew is a sufficient water source for the physiological activity of the microorganisms during the entire year. Already approx. 0.1–0.12 mm of dew activate the soil crust lichens during the night and the sun-exposed soil lichens photosynthesize 1–1½ h after sunrise before drying out (Fig. 3).

Rainfall in combination with cloudy weather extends the activity time for several hours. But high amounts of rain can suppress the photosynthetic CO_2 uptake of several soil lichens species, whereas cyano-lichens are able to take CO_2 from fluid water (e.g. Lange et al. 1995). The dew distribution within the dune field is inhomogeneous and depends on the interdune morphology, albedo and slope aspects. Deep hollows show a higher frequency of stable air layers at night time and consequently low dewpoint temperature differences and dark surfaces show more extensive radiation input at night. In winter, larger amounts of dewfall remain 1–2 h longer at the surface as compared to south-facing slopes, while in summer the duration of surface wetting shows no difference between the slopes (Fig. 4). The reason for this phenomenon is to be seen in the seasonally different radiation geometry of north- and south-facing slopes (Littmann and Kalek 1998). This indicates that especially deep interdunes and north-facing slopes are more favourable habitats for biological crusts. However, the frequency of dewfall is higher in summer than in winter, but does not contribute to enhanced crustal growth, as the critical time for crustal photosynthetic activity is limited by rapid drying after sunrise (Fig. 3; Veste et al. 2000).

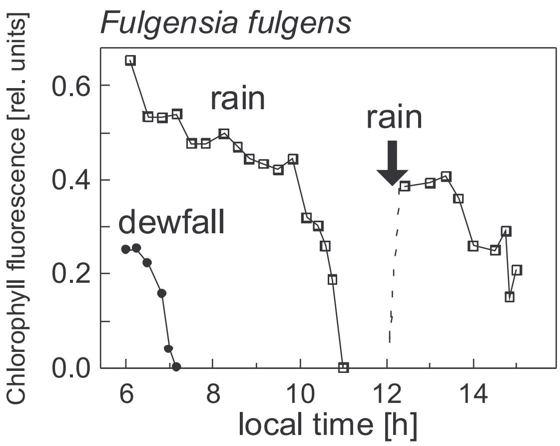

Fig. 3. Time course of photosynthetic activity in soil crust lichen *Fulgensia fulgens* after nocturnal dewfall (●) and rain (□). Activity was measured *in situ* with chlorophyll fluorescence

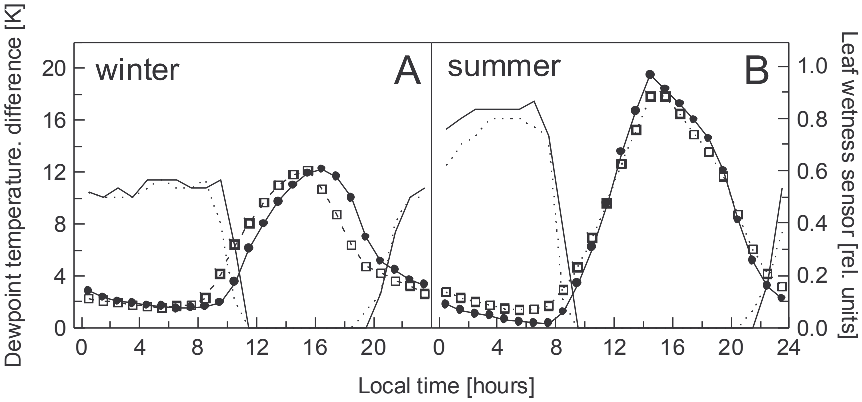

Fig. 4. Dewpoint difference at north-facing slope (●) and south-facing slope (□) and leaf wetness sensors on north-(solid line) and south-facing slopes (dashed line) in Nizzana

Nutrients

Arid and semiarid soils are low in nutrients, especially phosphorus and nitrogen (Buckley 1983, Evans and Ehleringer 1993). Under good water conditions there are indirect indications that nitrogen could limit plant growth even in arid regions (Floret and Pontanier 1982). In the sand dunes of Nizzana total nitrogen content directly under the biological crusts varied between 26 and 45 mg kg^{-1} (Fig. 5).

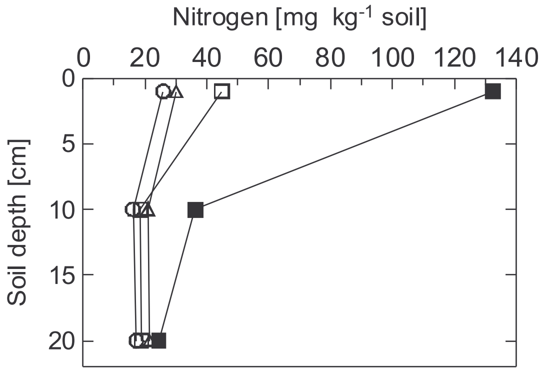

Fig. 5. Total nitrogen in the sand under different soil crust types in Nizzana (open symbols) and Haluza sand field (closed symbol). Sampling location: south-facing slope (O), interdune (△), north-facing slope (□), soil crust covered with cyanobacterial lichens (■)

Particularly under cyanobacterial lichen crusts, nitrogen content increased up to 132 mg kg^{-1} soil. The source of the nitrogen into the ecosystem can be either atmospheric deposition or biological nitrogen fixation by free-living or symbiontic cyanobacteria. The atmospheric nitrogen deposition in the sand dunes of the northwestern Negev is generally low and varies between 0.5 and 2 kg ha^{-1} a^{-1} (Littmann 1997, T. Littmann, unpubl. data). Under such conditions, biological fixation is an important nitrogen input source for the desert soils. West (1990) reported nitrogen-fixation rates of biological soils crusts from 2 to 41 kg ha^{-1} a^{-1}, while the atmospheric deposition in North American deserts is below 10% of this value (Evans and Ehleringer 1993) Even when the nitrogen fixation rates under natural conditions are still unclear and most of the measurements under laboratory conditions overestimate the fixation rates due to methodological problems (West 1990), the biological crust is a considerable nitrogen source in various desert ecosystems. Moreover, the biological crust contributes to the carbon input and soil development.

Hydrology

Crusting of soil surfaces generally leads to a reduction of infiltration and an increase in runoff. In sandy areas the infiltration rates of rainwater are normally high due to the coarse-grained texture of sand in comparison to loamy soil, where runoff is generated. However, on the sand dunes of the Negev runoff may occur after intensive rainfalls (Fig. 6; Yair 1990).

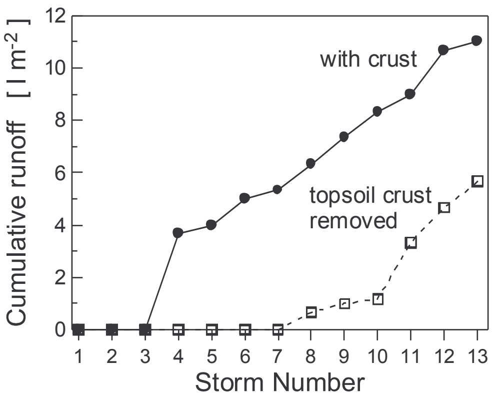

Fig. 6. Runoff yield on crusted plots (●) and plots where topsoil crust had been removed (□) in the Nizzana sand dunes.

Flow frequency and runoff rates were higher on the north-facing slopes than on the south-facing slopes in the Nizzana area. The lack of correlation between runoff volume and storm rain amount and peak rain intensity highlights several aspects. Runoff generation over microphytic crusts is often explained by the hydrophobic, water-repellent properties of the crust that greatly enhance runoff generation (Bond 1964; De Ploey 1977). It is clearly shown that the crust is able to absorb high water amounts when dry and infiltration decreases with time until the crust is saturated. A proper understanding of runoff generation in the area considered requires some knowledge regarding the combined physical-biological processes that take place under wetting conditions. An analysis of the pore size distribution shows the large predominance of pore diameters below 40 μ (Verrechia et al. 1995). Upon wetting two combined processes take place (1) water absorption and swelling of silty and especially clayey particles and (2) swelling of the microbiological elements. The filamentous sheaths may absorb water five to eight times of their dry weight and increase their volume up to ten times. Swelling of the biological elements from 2.5–4 μ to 20–50 μ is sufficient to fill up most of the voids. These combined processes result in a substantial decrease in crust pore size and limit water infiltration. However, infiltration is still high, because water can still infiltrate along the larger pores that remained unclogged. Results obtained by field experiments in Nizzana indicate that water uptake time, until saturation, is in the order of tens of minutes up to several hours. This relatively long time explains why under dry surface conditions short-intensity rain showers are unable to initiate runoff. The time factor for reaching saturation is far more important than the amount of rain. The biological properties and the biomass content of the topsoil influence the infiltration rates. Topsoils covered mainly by soil lichens shows the lowest infiltration (Fig. 7). Also in other arid ecosystems the limiting infiltration by the biological crusts are well known. In South Australia a soil lichen crust on sandy soil reduces infiltration by 50% (Rogers 1977). In the sand dunes of Nizzana the runoff frequency is relatively high in wet years, but runoff yields are low to very low. This is due to the very short duration, and limited rain amounts, of the effective rain showers.

Stability

The biological crusts enhance the aggregation of soil particles, and are thus a key feature for the surface stability. The filaments of cyanobacteria, excreted exopolysaccharides (Mazor et al. 1996) and fungal hyphae stick the sand grains together and prevent saltation. Surface stability is an important factor in deserts to prevent wind and water erosion (Booth 1941; Williams et al. 1995) as well the establishment and spatial distribution of higher vegetation (Kadmon and Leschner 1995). The fragile biological crust, and therefore the surface stability, are endangered by trampling of livestock, people and, in some deserts, by four-wheel -drive vehicles.

The effects of the disturbance of the crust on the entire ecosystem depend on the scale and frequency of disturbance. Small disturbances, like footprints, can be closed by the mobile cyanobacteria within days after rainfall, whereas disturbance like the removal of large areas of the biological crusts or frequent trampling needs years to recover. This will enhance sand erosion and desertification processes, as could be seen on the Egyptian side of the Sinai–Negev sand field, where trampling by goats and camels destroyed the biological crust and high-intensity sand dune mobilization led to a further decrease in vegetation cover.

Combating Desertification

The fixation of drifting sands is a major task in the frame of combating desertification. Several experiments have been made regarding this problem worldwide. Planting methods are a traditional means to control drifting sands and are widely practiced in the Middle East, Central Asia, China and North Africa. However, sand dune fixation by vegetation is only successful when wind speed is greatly reduced and sand movement is minimized. This will allow for the establishment of new vegetation and an increase in the surface roughness. Very often binding or liquid materials, e.g. petroleum products, clay material treated with polymers, are used to stabilize the sand surface (Veisov et al. 1999). From the environmental viewpoint these methods are unacceptable for sand fixation. For a more natural surface stabilization, the biological crust can play an important role. Sand dune mobility as well dune type and morphology depend on the wind direction and wind speed, which are largely controlled by the vegetational roughness (Tsoar and Møller 1986, Littmann and Gintz 2000). Planting vegetation or building up 20–30-cm-high pressed straw checkerboards will reduce wind speed. This will allow the biological crust to establish itself and in a feedback the surface stability will increase. This was sucessfully tested in the sand dunes of northern China to protect the Baotou–Lanzhou railway. Between the checkerboards a biological crust with lichens developed. Also in an experiment under natural conditions conducted in the Nizzana area, the biological crust recovered after nearly 3 years (Fig. 8).

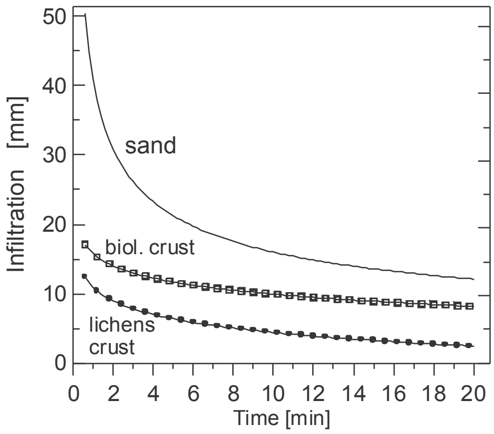

Fig. 7. Infiltration on sand, biological crust on north-facing slope and soil lichen crust in the Haluza sand field.

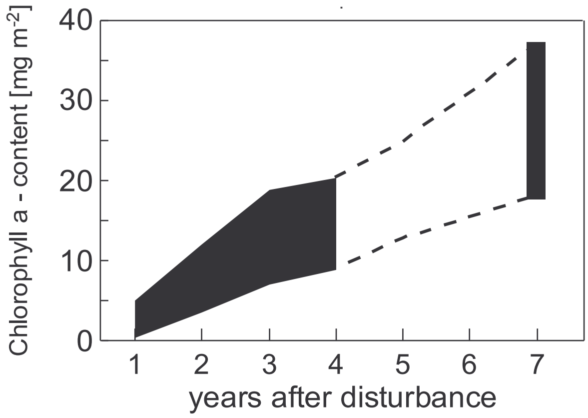

Fig. 8. Regeneration of the biological crust after topsoil crust was removed

After the disturbed topsoil is stabilized by a physical rain-crust, cyanobacteria are the first colonizers and they increase the stability of the topsoil. Only in later stages of the succession are soil lichens able to colonize the biological crusts (Eldrige and Greene 1994). Growth and succession depend on the microclimatic boundary conditions. Sufficient dewfall is important for the growth of microphytic crusts in deserts.

Conclusions

Micropyhtic crusts provide the only natural protective cover on the sand surface. An intact and living biological crust prevents wind and water erosion, enhances soil fertilization and is an important tool to combat desertification in arid, semiarid and subhumid regions.

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