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**Key Points:**

- Wind power is the dominant factor affecting the crust cover in Sde-Hallamish
- There is a critical disturbance area below which crust recovery is much faster
- Sde-Hallamish sand dunes become more active

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# The effect of wind and precipitation on vegetation and biogenic crust covers in the Sde-Hallamish sand dunes

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**Abstract** Vegetation and biogenic crust covers play an important role in sand dune stabilization, yet there is a lack of high temporal and spatial resolution data on sand dune cover. A field experiment, aimed at measuring the dynamics of biogenic crust and vegetation in sand dunes, was conducted at the Sde-Hallamish sand dunes in the northwestern Negev Desert, Israel, from July 2008 to August 2010. The climate of the Sde-Hallamish sand dunes is arid (the mean annual precipitation over the past 13 years is 61 mm), and the dunes are linear and partially stable, mainly due to the presence of biogenic crust and partially due to the presence of vegetation. In July 2008, 10 × 10 m plots on the four dune habitats (crest, interdune, north slope, and south slope) were treated as follows: (i) removal of vegetation and biogenic crust, (ii) removal of biogenic crust only, (iii) removal of vegetation only, (iv) partial removal of biogenic crust and vegetation, and (v) control plot. The surface coverage of sand, biogenic crust, and vegetation was monitored on a monthly basis, using a remote-sensing technique especially developed for the Sde-Hallamish sand dunes. It was found that strong wind events, with durations of several days, accounted for the coverage changes in biogenic crust and vegetation. The response to precipitation was much slower. In addition, no rehabilitation of biogenic crust and vegetation was observed within the experiment time period. The changes in biogenic crust cover were not necessarily related to changes in dune dynamics, since often an increase in biogenic crust cover is a result of wind erosion that exposes old crust that was buried under the sand; wind hardly erodes biogenic crust at all due to its high durability to wind action. The Sde-Hallamish dunes seem to have become more active as a result of a prolonged drought during the past several years. The field experiment reported here indicates that biogenic crust cover exhibits large seasonal variations that are not necessarily related to the growth of new crust but rather to the exposure of old buried crust.

## 1. Introduction

### 1.1. General Introduction

A substantial part of the world's land is covered by sand dunes (∼10%) [*Pye*, 1982; *Thomas and Wiggs*, 2008], mainly in the desert and coastal areas. Active dunes pose a serious threat to human property and activity as they can cover roads, houses, and agricultural fields [*Dong et al.*, 2005; *Khalaf and Al-Ajmi*, 1993]. In addition, unique ecosystems that are associated with active or fixed dunes may be altered as a result of dune activation/fixation and hence may lead to changes in biodiversity. A sand dune ecosystem is considered to be sensitive to human land use [*Tsoar*, 2008; *Veste et al.*, 2001].

The driving force of sand dunes is the wind. The rate of sand dune migration is proportional to the wind power, which is proportional to the cube of the wind speed [*Fryberger*, 1979], although *Claudin et al.* [2013] showed that a quadratic relation may be also appropriate (see Figure 2b of their paper). The activity state of a sand dune may also be affected by, for example, precipitation and evapotranspiration, as these affect vegetation and crust cover, which stabilize the dunes. On one hand, it is clear that in the absence of water (mean annual precipitation less than 50 mm), vegetation is almost not present, and hence, a dune can be bare and active, even when the winds are weak [e.g., *Tsoar*, 2005]. On the other hand, it has been demonstrated that a dune can be active even when the mean annual precipitation exceeds 1000 mm if the wind power is strong, suggesting that the wind is the main factor that affects dune mobility [*Tsoar*, 2005; *Tsoar et al.*, 2009]. For intermediate precipitation rates, both precipitation and wind are expected to play a major role in dune activity [*Yizhaq et al.*, 2007, 2009; *Ashkenazy et al.*, 2012].

  

Both experimental [e.g., *Pye and Tsoar*, 1990] and theoretical [*Bagnold*, 1941; *Andreotti et al.*, 2002; *Durán and Herrmann*, 2006; *Luna et al.*, 2009; *Reitz et al.*, 2010; *Nield and Baas*, 2008] studies have been devoted to uncovering the complexity of sand dunes. Yet, there are many open questions regarding the stabilization and remobilization of sand dunes, the relation between dune movement and biogenic crust and vegetation covers, the interplay between biogenic crust and vegetation development, and the mutual feedbacks between the climate system and sand dunes. Biogenic crust on sand dunes is usually found in arid and semiarid regions worldwide, and it covers substantial areas of the vegetated linear dunes in the Kalahari and Australian sand dunes [e.g., *Belnap and Lange*, 2001]. Thus, it is crucial to understand biogenic crust dynamics and its relation to vegetation and sand dynamics in order to fully understand the fixation and remobilization process of sand dunes in arid and semiarid regions.

### 1.2. Biogenic Crusts

Biogenic crust is typically a few millimeter thick, comprising several combinations of microphytic communities, such as lichens, mosses, fungi, soil algae, and cyanobacteria, and it is one of the main habitations of soil microbiota in semiarid and arid regions [*West*, 1990; *Belnap and Lange*, 2001; *Zaady et al.*, 2010]. The extent and primary colonization of biogenic crust in arid regions is a result of its remarkable ability to survive extreme dryness and temperature. Biogenic crust is considered as an "ecosystem engineer," as it affects the environment in various ways through, for example, water-holding capacity, soil moisture content, runoff generation, and water infiltration [*Hillel*, 1980; *Yair*, 1990; *Singer*, 1991; *Lange et al.*, 1992; *Eldridge et al.*, 2000; *Bowker et al.*, 2006]. Biogenic crust limits soil erosion by wind and water. It can withstand, in some cases, very strong winds (up to 30 m/s) [*McKenna Neuman and Maxwell*, 1999; *Argaman et al.*, 2006; *Ashkenazy et al.*, 2012] and long droughts and requires only a small amount of water to survive; it enters a dormant phase with a lack of moisture and quickly revives and develops under wet conditions. Enhanced soil erosion by water and wind has been associated with crust loss via anthropogenic activities [*Belnap*, 2003; *Bowker et al.*, 2006].

Precipitation affects both the formation and composition of the biogenic crust [*Zaady et al.*, 1997]. There are various factors that can affect the way that the soil crust community is developed, including climate, radiation intensity, topographic traits, granulometry and soil types, and soil structure. A recent study investigated the micromorphology and pedogenesis of biogenic crust [*Williams et al.*, 2012] and concluded that biogenic crust can "be considered critical agents in arid pedogenesis and landscape development."

Many studies have investigated the role of vegetation in dune stability [see *Pye and Tsoar*, 1990, and references therein]. For example, *Orlovsky et al.* [2004] monitored changes in biogenic crust cover in a protected area in central Asia and found that biogenic crust may change its role from having a positive effect on vegetation to having a negative one, suggesting that both undergrazing and overgrazing may be associated with desertification. Yet, only a few modeling studies have taken into account the role biogenic crust plays in dune stability in spite of its important role in dune stability and mobility in arid areas [see, e.g., *Kinast et al.*, 2013].

### 1.3. Goals and Rationale

The general aim of the present study was to improve our understanding regarding the role of biogenic crust and vegetation on dune stabilization/remobilization and regarding the relation of these processes to wind and precipitation. More specifically, the aim of the present study is to provide high temporal and spatial resolution data related to the development of various sand dune covers (i.e., vegetation, biogenic soil crust, and bare sand) and to study the relation between the changes in dune covers and changes in wind and precipitation. While previous studies have investigated the different aspects of biogenic crust in a sandy environment, there still seems to be a gap in the understanding of the seasonality of biogenic crust cover. The results reported below provide high temporal (monthly) and spatial (mm) resolution data on sand dune cover, including biogenic crust. The research area of Sde-Hallamish is a semiactive dune area that is subject to drastic changes in dune activity. Such a sensitive area is suitable to study the effects of different surface perturbations on dune stability. There are large annual fluctuations in rainfall and wind, activity which make the area a good place for studying the resilience of the ecological system.

Our theoretical rationale was to investigate the seasonal dynamics of sand dune cover, in general, and the role of biogenic crusts in stabilizing the soil surface, in particular, and to improve our understanding regarding the role of biogenic crust and vegetation on dune stabilization/remobilization and regarding the relation of these processes to wind and precipitation. To achieve this, we have performed a field experiment

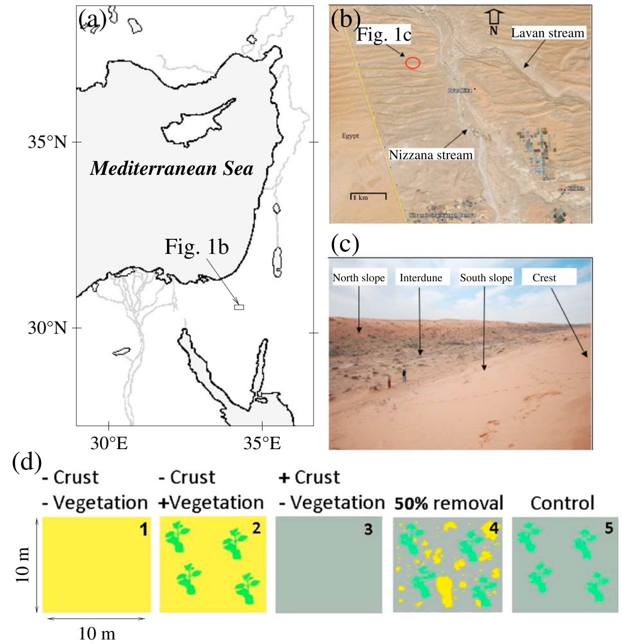


**Figure 1.** (a) The eastern Mediterranean area. (b) The area surrounding the research area (Google maps picture). The yellow line indicates the Egypt-Israel border; note that the Egyptian dunes are active (bright colors) while the Israeli dunes are semiactive or stable. (c) The research area–the four dune faces are indicated (two linear adjacent dunes are shown in the picture). (d) The treatments applied to each of the four dune habitats (crest, interdune, south slope, and north slope): 1, removal of crust and vegetation; 2, removal of crust only; 3, removal of vegetation only; 4, 50% removal of crust and vegetation; and 5, control. The green color represents vegetation, gray biogenic crust, and yellow bare sand.

in Sde-Hallamish, northwestern Negev Desert, Israel. We perturbed the different parts of a dune (north slope, south slope, interdune, and crest) by (i) removing both vegetation and crust, (ii) removing only crust, (iii) removing only vegetation, and (iv) removing about 50% of crust and vegetation. In addition, we monitored the dune cover in an undisturbed control plot. This set of treatments aims at (I) studying the pioneer dune cover when starting from a purely sandy plot (treatment (i)), (II) studying whether and how the existence of crust enhances/suppresses vegetation growth (treatment (ii)) and whether and how the existence of vegetation enhances/suppresses the crust development (treatment (iii)), and (III) how an “anthropogenic” disturbance (e.g., “trampling-like”) influences the recovery of the original dune cover (treatment (iv)).

## 2. Detailed Description of the Research Area and the Field Experiment

### 2.1. The Research Area

The Sde-Hallamish research site is located in the eastern extension of the northern Sinai erg (34°15′E, 30°55′N, Figure 1a), in proximity to the Egyptian-Israeli border, west and north of the Nizzana watercourse (Figure 1b). Sde-Hallamish is about 215 m above mean sea level (msl). The Sde-Hallamish sand dunes are vegetated linear dunes [*Tsoar et al.*, 2008; *Yair et al.*, 2008], while most of the dunes in the region are semiactive with an active dune crest (Figure 1c).

The research site is characterized by arid climatic conditions [*Littman and Berkoeics*, 2008]. Rainfall occurs during the winter season, November to March (with the exception of rare rain events that can occur during the other seasons). The region experienced large interannual and decadal variability with a mean annual precipitation of 107 mm for 1985–1995 and 60 mm for 1996–2006 [*Siegal*, 2009]. The annual mean precipitation from August 2007 to August 2012 was 51.3 mm.

In the winter, intense wind events are mainly associated with the Cyprus low synoptic system, a locally common winter low pressure system that produces southwesterly wind. In the summer, the winds are frequent (diurnal) and weaker and are associated with the diurnal sea breeze–the wind direction is northwesterly, perpendicular to the Mediterranean shoreline.

### 2.2. Previous Studies on the Sde-Hallamish Sand Dunes

*Kidron et al.* [2008] have studied the recovery rate of biogenic crust on the Sde-Hallamish sand dunes and along the rain gradient, along the Israel-Egypt border. They found, depending on the type of crust and measurements, that a full recovery time exceeds 5 years and can reach 22 years. We note, however, that partial crust recovery can be achieved within a few years, as happened on the Israeli side of the Israeli-Egyptian border, after the establishment of the border in 1982 [*Karnieli and Tsoar*, 1995]. Other estimates of biogenic crust recovery rates from various locations around the world range from a few years [*Johansen et al.*, 1984] to hundreds of years [*Belnap*, 1993] and even millennium [*Williams et al.*, 2012].

Crust was found to generate runoff on northwestern Negev sand dunes [*Kidron and Yair*, 1997; *Yair et al.*, 1997] and to affect the development of vegetation [*Yair et al.*, 2011]. In a recent study, *Veste et al.* [2011] investigated the vegetation and biological soil crusts along the Israel-Egypt border, along the rainfall gradient and found that the vegetation cover in the interdunes was around 28% with no significant difference along the climatic gradient. They reported increasing biogenic crust cover along the rainfall geographical gradient (from ~70 mm/yr in the south to ~150 mm/yr in the north), from ~40% in Nizzana (close to Sde-Hallamish) to ~90% in Yevul (the northernmost part of the gradient).

In an interesting field experiment in September 1996, *Yair* [2008] cleared a relatively large interdune soil cover (both crust and vegetation), in the vicinity of the field experiment area reported here; this experiment was also aimed at studying the dune rehabilitation time after a drastic perturbation. In a relatively short time (less than 3 years), a layer of physical crust developed on the disturbed area, with only minor signs of biological activity. Recovery of the biological components of the crust was observed in samples taken in August 2004, 9 years after the disturbance. *Yair* [2008] did not observe the recovery of perennial vegetation as of December 2012. *Yair* [2008] suggested two reasons for the absence of perennial vegetation: (i) the drastic surface disturbance, which removed the seed bank and uprooted vegetation, has led to a very long recovery time, and (ii) the properties of the crust developed a few years after the disturbance that limited the infiltration of water and thus the development of perennial vegetation. The field experiment reported here is different than that of *Yair* [2008] as, in our case, the disturbance only partially includes the seed bank in the upper soil layer.

The vegetated linear dunes of Sde-Hallamish may be divided into four habitats: interdune, south slope, crest, and north slope. These differ from one another by inclination, radiation absorption, and height. Previous studies discussed the differences between the different dune habitats [*Kutiel*, 1992; *Nevo*, 1995; *Kadmon and Harari-Kremer*, 1999; *Kutiel and Lavee*, 1999; *Sternberg and Shoshany*, 2001]. *Rummel and Felix-Henningsen* [2004] found that the north-facing slope had more bioturbation, more water content, and less radiation and evapotranspiration compared to the south-facing slope. *Yair et al.* [1997] suggested that areas with dense vegetation and thick biological crust, like that of the north-facing slope, could reduce lateral flow. *Jacod et al.* [2000] measured dewfall and found double the amount over the interdune compared to the south and north slopes. They associated this difference in dewfall with the presence or absence of biological crust.

### 2.3. Remote Sensing in the Northwestern Negev Sand Dunes

Based on a remote-sensing technique, *Karnieli and Tsoar* [1995] suggested that biogenic crust underlies the main difference in the spectral reflectance along the Israel-Egypt border (Figure 1b). This visual difference (that can be observed from space) followed the establishment of the Israel-Egypt border. In fact, such crust-sand differences between Israel and Egypt have occurred several times in the past, following changes in the political situation between the two countries. During the years after 1982, the year of the establishment of the Israel-Egypt border, Bedouins on the Egyptian side continued to exploit the area near the border, while this activity ceased on the Israeli side [*Tsoar*, 2008]. *Karnieli and Sarafis* [1996] identified the influence of phycobilin on the spectral reflectance of cyanobacterial soil crust and developed a crust index to be used with satellite images and aerial photographs. The vegetation cover classification of aerial photographs over 1956–2005 showed the relation between vegetation cover and the multiyear average precipitation [*Siegal*, 2009]. Here we used very high (a few millimeter) spatial resolution images to detect the cover fraction of biogenic crust, vegetation, and sand. We developed an automatic algorithm to analyze these monthly images and to study the temporal changes of the cover type from April 2008 to August 2010 (and, to some extent, until September 2012).

### 2.4. Description of the Field Experiment

The different dunes' habitats coincide with the different dunes' morphological units. The elevations of the four habitats in the research area (Figure 1c) are interdune (206 m above msl), south-facing slope (215 m above msl), north-facing slope (215 m above msl), and crest (220 m above msl). The interdune and crest habitats can be considered as homogeneous, while the higher elevation parts of the southern and northern habitats are sandier. Each habitat was subdivided into five plots, 10 × 10 m each, in which the distance between the plots is about 1 m (Figure 1d). These five plots, in each dune habitat (different dune areas), were treated, in May 2008, as follows: (1) removal of both biogenic crust and vegetation, (2) removal of biogenic crust only, (3) removal of vegetation only, (4) removal of ≈50% of vegetation cover and trampling of biogenic crust (grazing simulation), and (5) undisturbed control plot. Vegetation removal was performed by trimming the vegetation to the surface without touching the roots, as in heavy grazing. Crust removal (typically upper 10–20 mm and up to a depth of 100 mm) was performed by hand using a thin metal foil, such that the perturbation was relatively gentle.

The biogenic crust and vegetation were removed from an additional 3 × 3 m plot on the north slope in November 2009. This small plot was located on the lower part of the north slope and monitored on a monthly basis, together with the other research plots. This research plot was used to study the role of the disturbance size on crust and vegetation rehabilitation.

### 2.5. Measurements

Precipitation data were taken from the Kadesh-Barnea meteorological station, located about 4 km south of the field experiment site. We recorded the 10 min mean wind speed and direction in each dune face, using the YOUNG 03002 cup anemometer; the cup anemometers were located 3.5 m above the ground level. Following *Fryberger* [1979], the wind power was expressed using the drift potential (DP) as follows:

$$\mathrm{DP} = \langle U^2 (U - U_t) \rangle, \tag{1}$$

where $U$ is the wind speed (in knots: 1 knot = 0.514 m/s) approximated (see below) to a standard height of 10 m and $U_t$ is a minimal threshold velocity (= 12 knots) necessary for sand transport; the $\langle \cdot \rangle$ represents the time mean. The units of DP are vector units (VU). The 3.5 m wind measurements were transformed to 10 m using a logarithmic profile [*Gill*, 1982], which yielded a multiplication factor of 1.2; the logarithmic profile was based on a surface roughness of $z_0 = 18$ mm that we estimated in an environment similar to the dunes research area. The estimation of the surface roughness is based on measurements of winds from two different heights (3 and 10 m) from a region with vegetation cover similar to the Sde-Hallamish sand dunes.

The temporal changes in the plot covers were monitored using very high resolution images that were taken on a monthly basis, from July 2008 to August 2010, using a digital camera (NIKON D80, with a lens of 10 mm focal length) from an elevation of 5 m above the plot surface. Two images (southern and northern halves) were acquired to cover the full plot size. These images were analyzed using a specially designed algorithm (see Appendix A), which was validated using ERDAS software. The validation was performed by classifying the images using ERDAS and then comparing the results to the figures classified by our algorithm. The total accuracy (i.e., the ratio between the number of correctly identified pixels to the total number of pixels) of 10 randomly selected images was between 72% and 97%.

By using the specific signatures of biogenic crust, bare sand, and vascular vegetation, we monitored, calculated, and mapped all the plots as a function of time. Other algorithms/indexes [e.g., *Karnieli and Sarafis*, 1996] for classifying crust from aerial photographs did not yield good results for the RGB camera pictures that we used, probably because these algorithms were tuned to pictures with resolutions that are order of magnitudes coarser than ours. The algorithm we developed excludes small vegetation patches (less than a few centimeters wide) and thus provides only the lower bound estimation of vegetation cover when, in fact, the actual vegetation cover can be larger.

## 3. Results

### 3.1. Vegetation, Crust, and Sand Covers

Figure 2 depicts the sand, crust, and vegetation cover percentage in all control plots from July 2008 to August 2010; the monthly DP and rainfall in the research area are also included. As expected from the relatively strong winds and the mobility of sand over the crest, biogenic crust was absent in all crest research

  

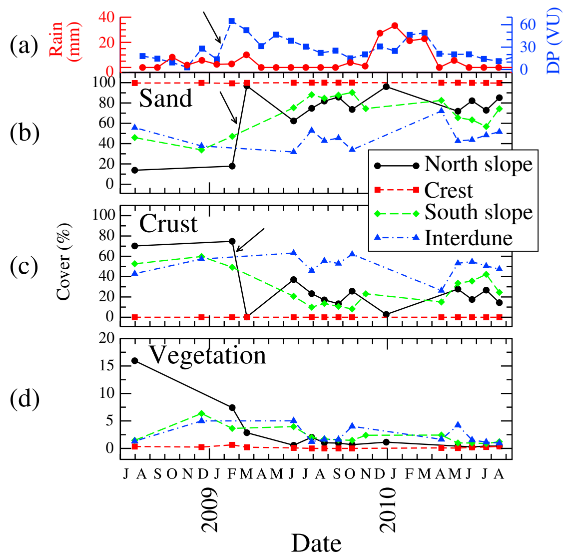


**Figure 2.** (a) DP (squares) and precipitation (in millimeter/month, circles), (b) sand, (c) crust, and (d) vegetation cover percentage in the control plots from July 2008 (date of treatments) to August 2010. Note the absent of crust in the crest habitat plot. The black, red, green, and blue lines indicate the north, crest, south, and interdune habitats, respectively. The arrow in Figure 2a indicates the wind storm that resulted in increased sand cover (indicated by the arrow in Figure 2b) and decreased biogenic crust cover (indicated by the arrow in Figure 2c).

plots. The percentage of vegetation cover in these plots is very low, and therefore, sand cover fluctuations are undetectable. In the interdune control plot, the percentage of sand cover (i.e., the percentage of pixels that were identified as sand) is about the initial one, with fluctuations of 25% during the research period. South and north slope control plots exhibited an increase in sand cover. A large decrease in crust cover percentage was observed after February 2009, in the south plot and, especially, in the north plot. Interestingly, this increase in sand cover (from ~20% to ~80%), in the control plot of the north slope, suggests that storms during February and March 2009 (associated with the high DP during these months) triggered the activation of the north slope (and, to a lesser degree, the south slope) that continued until the end of the research period. Figure 2 also depicts vegetation cover, and it is clear that vegetation is less dominant in the research area as its coverage is less than 10%, except at one point. The low contribution of vegetation to the land cover was discussed previously [*Tsoar*, 2008; *Yair et al.*, 2008; *Veste et al.*, 2011; *Siegal et al.*, 2013]. Our estimation is closer to the estimation of *Siegal et al.* [2013] who reported a low mean vegetation cover of 5–12% in Sde-Hallamish during 2007–2009, due to drought.

A decrease in crust cover was observed during the research period (Figure 3). The north slope had the most extreme decrease around February–March 2009. The south slope exhibited a decrease in crust cover from February–March 2009 to December 2009 in plots 3, 4, and 5. Generally, these plots had less crust cover at the end of the research period (August 2010) compared to the beginning (July 2008). The plots in the north and south slopes showed equivalent changes during the study period.

An increase in crust cover (Figure 3) was observed in the interdune plots where crust was removed (plots 1 and 2). Most of this increase was not a result of crust development but was due to wind erosion. *Allgaier* [2008] showed that removal of vegetation could cause an increase in transported sand. In our case, the removal of crust and vegetation in plot 1 and the removal of crust in plot 2 contributed to the exposure of older crust layers buried underneath the sand.

Several reasons support the claim that the increase in crust cover was due to wind erosion and exposure of old crust. First, the crust was removed at the end of July 2008, while "new" crust was detected as soon as mid-December 2008. Only partial biogenic crust recovery is possible within such a short time [see *Kidron et al.*, 2008]. Moreover, three dry months followed the treatment, and there were only two rainfall events in the 2 months just before mid-December (Figure 4), leaving a very short time period for the reestablishment of biogenic crust. In addition, we found that as a result of wind erosion, plots 1 and 2 had a several centimeters lower elevation than their surroundings, and they were lower than they were 5 months earlier (after performing the initial perturbation); we did not observe such lowering in the other plots. Apparently, after the crust removal, the research plot was more exposed to aeolian activity. Qualitatively, the sand covered plots 1 and 2 during the spring and summer of 2009, and they were eroded again by wind a year later.

### 3.2. Effect of the Area Size of the Plot on Rehabilitation

Table 1 summarizes the development of biogenic crust and vegetation in the 3 × 3 m plot described in section 2.4. We observed a sharp increase of crust after only 1 month; the precipitation during this month of recovery was very high, 27.3 mm (Figure 4). There is a substantial difference between the crust development of this plot compared to the northern plot where vegetation and crust had been removed (plot number 1)—an establishment of 38.5% of crust after only 1 month in the small plot, compared to the

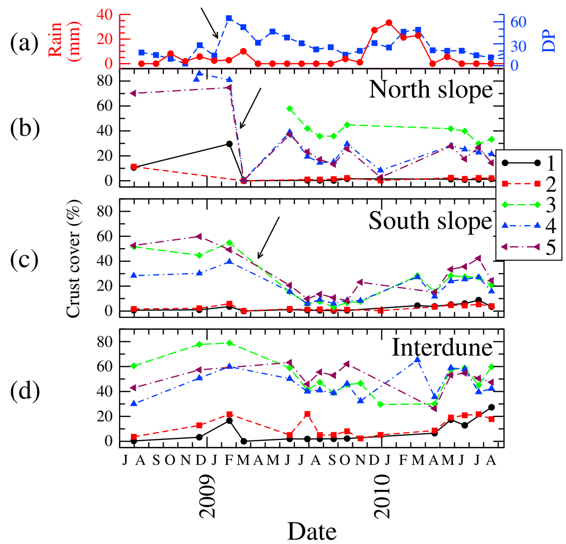


**Figure 3.** (a) DP and precipitation (in millimeter per month), crust cover percent in the (b) north slope, (c) south slope, and (d) interdune. Black, red, green, blue, and maroon lines indicate plots 1 to 5, respectively. Each plot had different treatments (July 2008: date of treatments) as described in the text and depicted in Figure 1 as follows: 1, removal of vegetation and biogenic crust; 2, removal of biogenic crust only; 3, removal of vegetation only; 4, 50% removal of vegetation and biogenic crust; and 5, control. The arrow in Figure 3a indicates the wind storm that resulted in decreased biogenic crust cover mainly in the north and south slopes (indicated arrows in Figures 3b and 3c).

insignificant recovery of crust in the larger, 10 × 10 m, north plot. We note, however, that the crust that developed shortly after the disturbance on the small plot may be a physical crust (due to the impact of rain drops) without the biological characteristics of biogenic crust—the new crust looked much brighter than the dark-green crust in the control plot. Yet, polysaccharide and chlorophyll levels of samples, taken in August 2011 from the small treated plot, were measured at the Gilat Research Center, and the levels were similar to those of the control plot, indicating the recovery of biogenic crust.

### 3.3. Comparison Between Habitats

We also investigated the effect of height and slope aspect on crust cover for the south, north, and interdune control plots. As mentioned above (section 2.5), each 10 × 10 m plot was divided into northern and southern parts. We found that the south-facing slope of the control plots exhibited large differences between the two halves (typically 20%), with a crust cover fraction in the southern half (lower by ≈2 m) that was systematically higher than in the northern (higher) half. In the interdune and north plots, on the other hand, the fraction of crust was approximately similar in the two halves. This finding is in agreement with the study of *Yair et al.* [2008]. Generally, prior to the treatments, the north-facing plots were covered with thick crust, including the higher parts of the plots, and the south-facing slope plots had thin crust only on the lower half of the plots.

It is possible to estimate the spatial variability of the surface cover detected by our algorithm by comparing the southern and northern parts of the interdune habitat (see also Appendix A). In Table 2, we summarize the mean and standard deviation of the different treatments of the interdune habitat. It follows from this table that the error in the estimation of the surface cover is less than 13%. We did not implement the same analysis for the crest habitat as it is almost entirely bare sand and, thus, would reflect very small spatial variability.

Because radiation absorption is higher on the southern slope (as it is facing the sun), one expects to observe more vegetation cover in the north-facing plots compared to the south-facing plots, since radiation eventually increases evaporation. We observe significantly larger vegetation cover in the northern control plot at beginning of the research period (see Figure 2d). However, when looking at the results of the last 5 months of the research period, it is noticeable that the northern slope had less vegetation cover on plots 1, 2, 3, and 5 compared to the southern and interdune plots, and that the differences between plots where crust was removed and plots where it was not removed is larger in the northern habitat (Table 3).

Except for the crest, we find that the northern slope plots had the smallest vegetation cover, in spite of the favorite growth conditions on this part of the dune. The reason might be the sand accumulation effect that was detected during this period of study, as moving sand can affect the germination successes of annuals and other plants that need a stable surface.

Plots 1 and 2 exhibited similar vegetation cover in all habitats except the crest, despite their different treatments. The crest of the dune was active, and no crust was found during the research period. Annuals and perennial plants were occasionally buried under the sand, and wind erosion uncovered vegetation roots quite often.

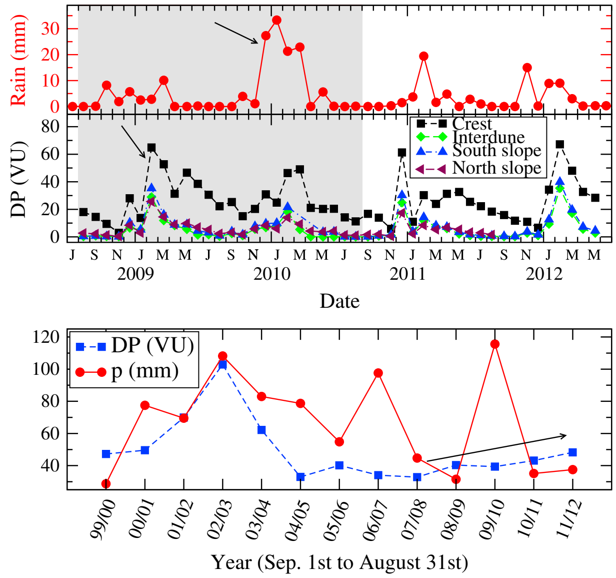


**Figure 4.** (top) Monthly rain (mm). The arrow indicates the rare wet winter season. (middle) Monthly DP (in VU) at the crest, interdune, south slope, and north slope from August 2008 to May 2012—the research time period is indicated by the gray shading. Note that the DP in slopes and the interdune is much smaller than at the crest. The annual DP can be obtained by summing the DP of the different months and is (for the research time period, August 2008 to August 2012): ≈323, ≈60, and ≈75 VU for the crest, interdune, and slopes, respectively. The arrow indicates the strong wind storm of the beginning of 2009. (bottom) The annual DP (blue) and rain (mm, red) at the nearby Kadesh-Barnea meteorological station, from the 1999–2000 to 2011–2012 seasons. Note the moderate increase in DP since 2007–2008 (indicated by the arrow) and that four out of the five recent years were very dry.

As expected, the control plot in the interdune had the largest crust cover percentage during most of the research time (Figure 2). Plots 4 and 5 in the north-facing slope (Figure 3) had the most significant decrease in crust cover that started during February–March 2009 and continued with a lower cover fraction compared to the beginning of the research.

As discussed above, we found a significant increase in crust cover (~20%), after a relatively short time, in plots 1 and 2 of the interdune, and about the same amount at the end of the research period (Figure 3). We did not observe similar changes in the other habitats and treatments. This change happened only in the interdune, where, apparently, there were buried laminas of crust and sand (see below).

### 3.4. Mechanisms for Change in Dune Cover: Extreme Wind Events and Precipitation

Rain and wind seem to be the main climatic factors that affect the development of biological crust and vegetation (hence sand cover). Naturally, reduced rain leads to reduced vegetation growth. Strong wind erosion causes vegetation suppression—the shifting sand leads to root exposure, plant burial, and leaf damage (partly due to sand movement by saltation). Wind can lead to the erosion of biogenic crust (in particular, at the sand-crust interface) and coverage of biogenic crust by sand. The role of vascular vegetation and crust (physical and biological), in terms of sediment transport, is very important. Resistance to wind erosion is higher in soils that are covered with biogenic crust [*Belnap and Gillette*, 1998]. Sandy soils (not sand dunes) dominated by vegetation and well-developed biogenic crust had less sediment movement and disturbance by trampling, especially during dry and windy years, as well as increased sediment transport and reduced biological and physical crust cover [*Belnap et al.*, 2009]. *Breshears et al.* [2009] showed an increased sediment transport with high disturbance and low woody plant canopy cover. A cover of 17% of vascular vegetation (without biogenic crust) over the interdune habitat in the Nizzana sand dune field can decrease sand transport to less than 1% compared to sand transport when vegetation is absent [*Allgaier*, 2008].

Vegetation and crust covers fluctuated during the research period, where the strongest fluctuations of crust cover were observed in the control plot and plot 4 of the north slope (Figure 3). A sharp decrease in crust cover was found around the months of February and March 2009 (Figure 3), and vegetation declined toward July 2009. Figure 3 also depicts an increase in crust cover in plots 1 and 2 over the interdune habitat, from August to September 2009.

**Table 1.** Summary of 3 × 3 m Small Plot Results[a]

| Date | Vegetation (%) | Sand (%) | Crust (%) |
|---|---|---|---|
| 24.11.09 | 0.4 | 98.6 | 1 |
| 29.12.09 | 0 | 61.5 | 38.5 |
| 18.8.10 | 3.8 | 69.8 | 26.4 |

[a]Vegetation, sand, and crust covers (3 × 3 m small plot) on 24 November 2009 when the crust and vegetation were removed, 1 month after and at the end of the research.

The changes in sand, vegetation, and crust covers may be associated with changes in wind (or DP) and rain (Figure 4). The research period included two rainy seasons (winters), in which the winter of 2008/2009

  

**Table 2.** Cover (%) of Northern and Southern Halves of the Interdune Plots[a]

| Treatment / Cover | Vegetation (%) | Sand (%) | Crust (%) |
|---|---|---|---|
| 1 | −0.08 ± 0.43 | −2.29 ± 4.82 | 2.37 ± 4.85 |
| 2 | −0.12 ± 1.78 | 6.54 ± 12.98 | −6.42 ± 12.50 |
| 3 | −0.14 ± 2.59 | 19.41 ± 13.04 | −19.27 ± 12.94 |
| 4 | 1.56 ± 6.77 | 0.07 ± 8.84 | −1.64 ± 9.24 |
| 5 | 1.23 ± 2.95 | 9.67 ± 7.91 | 8.44 ± 7.69 |

[a]Temporal mean (from August 2008 to August 2010) ± standard deviation (%) of the difference between northern and southern halves of the interdune habitat for vegetation sand and biogenic crust covers. Brief treatment description: 1, vegetation and crust removal; 2, crust removal; 3, vegetation removal; 4, partial vegetation and crust removal; and 5, control. The maximal standard deviation is 13.04%.

was drier (31.4 mm) than the consecutive year (109.9 mm), which had an extremely wet winter. The precipitation during the winters of 2010/2011 and 2011/2012 measured about 35 mm and during 2007/2008, 44.7 mm (Figure 4). In contrast, the DP was higher during the winter of 2008/2009 than in the winter of 2009/2010. The highest peak of DP (64.8 VU) was around February and March 2009, the same time when crust cover was declining in the northern control plot.

There was an increase in vegetation cover during 2010 that can be attributed to the high precipitation that enhanced the growth of annual plants. The lower DP during winter 2009/2010 might have had some contribution to this increased vegetation cover. The enhanced response to intense rain events is a common phenomenon found in annuals. In January 2010, at the beginning of the rainfall events (Figure 4), the seeds that were hidden in the sand germinated and increased the vegetation cover, similar to previous studies [*Evenari et al.*, 1982; *Gutterman*, 2002]. It seems that high vegetation cover lasted until the summer. The reason for this observation may be related to our algorithm that searches for dry and brown vegetation, and annuals can stay attached to the soil for long periods of time, even after becoming dry. As expected, the effect of increased precipitation on the perennial shrubs over all the research plots was not noticeable. The response time of these shrubs is much longer than the 2 years of this study, such that their effect on dune cover can be detectable only after a longer period. A large amount of rain can also result in a new physical crust that increases the surface stability. Weak winds and continuous rain events may help to establish new biogenic crust.

We showed that high wind power (erosion) can alter the vegetation and crust surface cover in a relatively short time. This can cause a serious threat to vegetation and to biogenic crust that need to be exposed to sunlight in order to reproduce. Another example of the wind power effect is the rediscovered crust in plots 1 and 2 over the interdune habitat by wind erosion (bottom panel of Figure 3) and its coverage by sand.

**Table 3.** Summary of Vegetation Cover (%)[a]

| Treatment / Habitat | Interdune (%) | South (%) | Crest (%) | North (%) |
|---|---|---|---|---|
| 1 | 7.32 | 7.23 | 1.71 | 3.94 |
| 2 | 7.47 | 8.19 | 2.52 | 3.72 |
| 3 | 7.6 | 9.93 | 4.7 | 6.11 |
| 4 | 10.93 | 10.66 | 2.14 | 14.42 |
| 5 | 15.64 | 13.04 | 0.67 | 9.61 |

[a]Median vegetation cover (in %) of all plots and treatments from August 2008 to August 2010. Brief treatment description: 1, vegetation and crust removal; 2, crust removal; 3, vegetation removal; 4, partial vegetation and crust removal; and 5, control. The data are based on an algorithm that is more sensitive to vegetation.

## 4. Discussion

We developed an automatic parallelepiped supervised classification for distinguishing between crust, sand, and vegetation covers on sand dunes. Images and recognition data had a very high spatial resolution of a few millimeter, enabling us to detect small changes in the plots. We detected the changes in our research site on a monthly basis (or more infrequently) and found large variabilities of sand, crust, and vegetation covers (Figures 2 and 3). These changes can be very drastic, mainly due to intense wind events (Figures 2a–2c, 3a, and 3b). Strong winds can lead to coverage of crust and vegetation by sand but can also expose buried crust by wind erosion. Intense winds can alter vegetation and crust covers in a relatively short time, unlike the effect of rain which is much slower. Furthermore, in some cases, the effect of winds on dune cover may overcome the effect of rain. The time required for the detection of changes in perennial shrubs, especially after a rainy season, is even longer. Thus, two time scales may be associated with the dynamics of sand dune cover—fast (wind) and slow (precipitation) where, in many cases, the former is the most dominant one.

We saw that the small 3 × 3 m plot exhibited a very fast crust recovery rate (about 1 month) compared to the other plots in the northern slope of the dune (Table 1). The small size of this plot may have a critical influence on the change in cover and may suggest the existence of a critical disturbance size for crust development. We suggest three possible reasons for this difference:

1. Recovery via secondary succession. The area of disturbance (9 $m^2$ compared to 100 $m^2$) affects the rehabilitation time since, in a small disturbance, seeding crust particles from the periphery can "diffuse"/"percolate" more easily into the disturbed plot.
2. The recovery process of the small plot may be similar to the ones discussed in Figure 3 for which the wind eroded the sand from the plot and exposed an old crust layer.
3. Intense rains that created a physical crust. The second, however, is unlikely as we did not observe changes in the elevation of the plot and since even low vegetation (of about 0.3 m height) may shield such a small plot from the wind. Such a fast recovery, during the same time period, was observed in other small plots along the Israel-Egypt border (not described here). The third is also unlikely as intense rain should have also resulted in physical crust in the larger 10 × 10 m plots. The question of the crust recovery time, as a function of the disturbance area size, is interesting and requires further experimental and theoretical studies [see *White and Jentsch*, 2001; *Yizhaq et al.*, 2013].

For the research time period, we did not detect drastic changes in the plots as a result of the treatments (besides the reexposed crust in plots 1 and 2 over the interdune)—future monitoring is required to observe rehabilitation. The seasons after the research period were crucial for the changes that took place (which we only partially measured). The precipitation during the 2010–2011 and 2011–2012 seasons was very low (about 35 mm/yr), while DP, calculated based on data from the nearby Kadesh-Barnea meteorological station, exhibited only a slight increase (Figure 4). This increase is also noticeable in the DP in the research area where the winters have become windier since the beginning of 2010. Analysis of the control plot during the summers of 2011 and 2012 indicates that the control plots of all habitats have become more bare and active (Figure 5). The interdune exhibited the most extreme change, with 90% sand cover during September 2012, compared to only 60% maximum sand cover during the summers of the previous 4 years. Our impression is that the Sde-Hallamish dune field became more active and that the dune slopes also turned active; the drought of the past few years and the apparent increase in wind power most likely underlie this increase in dune activity.

The dune cover had large seasonal variations (Figures 2 and 3). This fact may have implications for the estimation of dune activity and for the use of dune mobility indexes [*Thomas et al.*, 2005]. Measuring the dune cover during the winter time will probably lead to large uncertainty since the dune is most active then, as a result of a few intense wind events. The dune cover is more stable during the summer, and thus, it seems to be a more suitable time for dune cover measurements. We note, however, that the dune cover during the summer may be significantly different from the winter one. It is recommended to monitor the dune cover (at least 6 times a year) in dynamical sites, such as Sde-Hallamish to uncover the magnitude of the seasonal variability. Less frequent monitoring may yield erroneous conclusions regarding the sand dune cover.

The field experiment reported here suggests that increased crust cover is not necessarily linked to the rehabilitation of the biogenic crust and the increased stability of the dune, since it can be attributed to

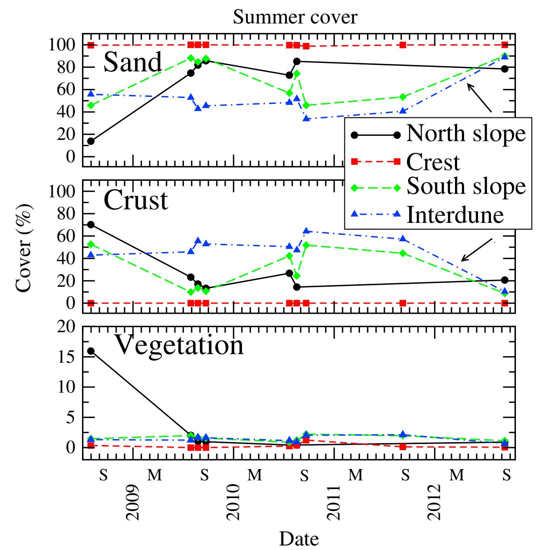


**Figure 5.** (top) Summer sand, (middle) biogenic crust, and (bottom) vegetation covers in the control plots, from August 2008 to September 2012; M, March; S, September. Note the unusually high sand cover (especially in the interdune) during September 2012, possibly reflecting the increase in dune activity in Sde-Hallamish (indicated by the arrows).

an exposure of old crust that was buried under the sand blowing from the higher parts of the dune. Thus, paradoxically, the increased crust cover, in this case, reflects, in fact, enhanced dune activity. Based on this observation, we conclude that trends in biogenic crust cover do not necessarily reflect trends in dune activity. We did not find parallel observations for vegetation.

Recent modeling studies [*Yizhaq et al.*, 2007, 2009] have suggested the bistability of vegetation cover on sand dunes under given climatic conditions. Our recent modeling studies suggest a similar bistability for crust cover on sand dunes [*Kinast et al.*, 2013]. The field observations reported here support this prediction, as nearby plots 2 and 3 (with 1 m distance between them) on the north slope had quite different soil surface coverage, with zero crust cover for plot 2 while plot 3 had more than 40% crust cover (see Figure 3b). Such bistability also occurred, to a lesser degree, in the interdune (Figure 3d), but a longer study is needed to confirm this conclusion.

## 5. Conclusions

In summary, the conclusions of the present study are as follows:

1. Wind power is the dominant factor affecting the crust cover on the linear sand dunes in the Sde-Hallamish sand dunes. Rainfall is essential for the vitality of vegetation and crusts. However, there is a lag between the input of rainfall and its consequences, while the effect of wind erosion is instantaneous. In other words, there are two main time scales that may be associated with the dune dynamics: (1) a fast one (seasonal) that may be linked to extreme and short wind power events (and hence to dune mobility) and (2) a slow one (years) that may be linked to precipitation (and to perennial shrubs and grass that suppress sand mobility).
2. The plots, covering an area of 100 $m^2$, where vegetation and/or crust were removed, did not recover during the 2 years of the research. A smaller plot (area of 9 $m^2$) experienced a relatively fast crust recovery. Hence, there is a critical disturbance area below which the crust recovery is rapid. We suggest either that the diffusion processes of crust particles are more effective in a small disturbed area or that a small disturbed area is not as exposed to severe erosion as larger disturbed areas are. Therefore, we assume that crust will develop in areas where wind erosion of the dune sand is minimal.
3. Most of the sand dune activity occurs during winter and springtime when the wind power reaches its peak. Summer has fewer changes in perennial vegetation and crust cover because of reduced wind power.
4. Increase in crust cover may be due either to the exposure of buried crust or to the development of new crust. Hence, changes in crust cover do not necessarily reflect changes in dune activity. Moreover, changes in crust cover may be very rapid as a result of intense wind events that cover/expose the crust, unlike vegetation, which is less drastically influenced by extreme wind events.

  

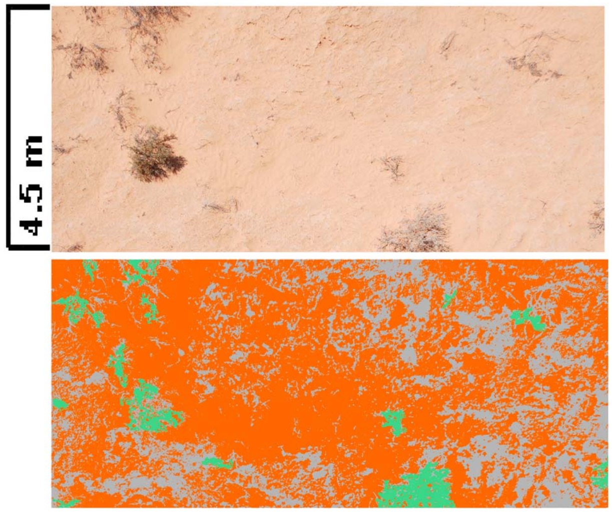


**Figure A1.** Example of a successful classification. (top) Original image. (bottom) Classified image. The green, gray, and red colors indicate vegetation, crust, and sand, respectively. This image was taken in June 2009 from the control plot in the south slope.

These conclusions can be further summarized—rapid changes in dune cover occur mainly during winter and are often associated with strong and rapid wind events. Variations in dune cover are not necessarily related to the stabilization process of the dunes.

## Appendix A. Classification Algorithm

The algorithm used to identify the different dune cover involves many details that are out of the scope of the present study and are described elsewhere [see *Amir*, 2011]. We aim here to describe the general guidelines of the algorithm. The algorithm was built and calibrated to the Sde-Hallamish sand dunes using the D80 Nikon camera with a 10 mm wide lens.

The classification process consists of the following six stages:

1. Examination of all image files for disqualification pictures. We excluded images taken under clouds and sunset conditions. In addition, images that were taken when the sand was wet were excluded because the algorithm did not yield good results under these conditions. Such conditions were rare. We identified wet ground by inspecting darker colors after rain events.
2. Geometric correction and subtraction processes.
3. Average correction processes: we calculated the average value of each (red, green, or blue) band and compared it to the reference band. The difference between the reference band and actual figure was added or subtracted, to make the averages equal. This step reduced the changes in appearance caused by changes in sunlight.
4. Class recognition. The algorithm associates each pixel with a certain class (vegetation, crust, sand, or other). The algorithm searches for vegetation by identifying picture areas that are more spatially variable and have darker colors. Then the algorithm searches for crust and sand using the sum of RGB colors and the difference between red and blue (motivated by *Karnieli and Sarafis* [1996]).
5. Inspecting visually the classification results and removing unsuccessful ones.
6. Statistical estimation of the classification results.

The main part of the classification process is the recognition process (stage 4 above). The first stage is a series of searches for pixels and their surrounding pixels for the existence of vegetation properties: vegetated areas are more spatially variable than those of crust and sand. We use this fact to identify vegetated regions. The result is a matrix of zeros for sand and crust, and ones for vegetation. To avoid the noise of small objects, such as stones, fissures, and stratums in the crust and sand, or individual pixels that have been misclassified, we had to "sieve" the classified pictures as follows: all small objects (classified as vegetation) under a specific threshold were removed. In the next stage, the algorithm tests the nonvegetation pixels and determines whether they can be classified as crust or as sand. This is done by a dynamic threshold:

an optimal polynomial function that distinguishes sand and crust based on the sum of RGB values of the pixel and the difference between red and blue. Figure A1 depicts an example of the classification outcome of the control plot in the southern slope. Images of unsuccessful classification were excluded from the final results. For each plot we had at least 12 successful classifications (from different dates) during the research period (August 2008 to August 2010).

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