Aeolian Research 15 (2014) 261–267

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Wind speed determines the transition from biocrust-stabilized to active dunes

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ARTICLE INFO

Article history:
Received 21 December 2013
Revised 25 April 2014
Accepted 25 April 2014
Available online 21 May 2014

Keywords:
Biological soil crust
Drift potential
Erodibility
Sand dune
Negev Desert

ABSTRACT

We examine the hypothesis that above a certain height, crusted, stabilized dunes become non-crusted with a mobile crest. Toward this end, twelve plots, 10 × 10 m, were demarcated along a 1 km-long transect in the Nizzana research site (NRS), western Negev, Israel, extending along a ridge of a dune from the crusted interdune up to a height of 22 m above the interdune, characterized by a non-crusted mobile crest. Within each plot, a 4 × 4 m subplot was established where the upper 3 cm of all surfaces was removed. Surface stability was monitored using six erosion pins from March 2010 to February 2012. In addition, data from a nearby meteorological station were analyzed. The data indicated that drift potential (DP) was the highest during winter and spring. A good correlation (with $r^2 = 0.73$) was found between the monthly DP and the absolute change in pin height. Also, a good correlation (with $r^2 = 0.85$) was found between altitude and the absolute change in pin height. A monthly change in pin height of ~0.3 cm marked the threshold between the crusted and the non crusted sections of the dune, which corresponds to 8 m above the interdune. The findings imply that as long as the absolute monthly change in pin height is <0.3 cm, crust establishment may take place. The findings point to the capability of the crust to cope with limited surface instability and to the potential of biocrusts to serve as biomarkers for surface stability.

1. Introduction

Surface stabilization may probably be regarded as the most important role played by biocrusts (known also as microbiotic crusts or biological soil crusts). This is especially crucial for dune sands which due to their low cohesiveness are prone to easy mobilization by wind (Gillette et al., 1980; Hesse and Simpson, 2006). While dune mobility is often measured based on air photos or satellites (Bullard et al., 1995; Levin and Ben-Dor, 2004; Hugenholtz and Wolfe, 2005; Rubin et al., 2008), or experimentally studied under controlled conditions using indoor (Dong et al., 2003; Zheng et al., 2003; Li et al., 2004) or outdoor (Leys and Eldridge, 1998; Sherman and Farrell, 2008; Maurer et al., 2010) wind tunnels, field measurements under natural conditions are less common.

Sand traps are often used to measure sand deposition or flux (Fryberger et al., 1984; Arens and van der Lee, 1995; Ellis et al., 2012). The use of erosion pins is however far more common. With negligible obstruction to sand movement, they facilitate monitoring of deposition as well as erosion (Jungerius and van der Muelen, 1989; Arens, 1996; Lancaster and Baas, 1998; Arens et al., 2004; Ben-Dor et al., 2006; Levin et al., 2006; Hugenholtz et al., 2009). They may be especially suited for measuring annual sand movement and surface stability at dune fields with low or partial mobility, where wind power is not high enough to detach or burry the pins within a short time span.

This research focuses on the partially crusted Hallamish dune field in the western Negev Desert where biocrusts inhabit substantial sections of the dunes (Kadmon and Leschner, 1994; Kidron et al., 2009). In the Nizzana research site (NRS) at the Hallamish dune field, the crusts cover all the sandy interdunes and the mid and bottom slopes of the dunes. They are absent only from high-elevation and mobile crests. These dunes are considered active. Crusts however cover the slopes and crest of a low dune which is therefore considered stabilized. It is hypothesized that under the current precipitation and wind regimes, wind power is too strong to allow for crust establishment at the high-elevation crests. It is however sufficiently weak to facilitate crust establishment at the low-elevation crests.

Previous research using sand traps and erosion pins on intact surfaces supports the above hypothesis. While the non-crusted

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http://dx.doi.org/10.1016/j.aeolia.2014.04.006
1875-9637/

crests of the active dunes experienced high rates of sand deposition and erosion, footslope positions with low deposition exhibited high biocrust cover (>90%) while midslope positions with intermediate deposition values experienced a patchy (25–75%) crust cover (Kidron et al., 2000, 2009). Nevertheless, these measurements were confined to the natural surfaces, whether crusted or non-crusted, and therefore could not have explored the potential erodibility of the surface (and hence its potential suitability for crust establishment) prior to crust establishment. The current research aims to explore the potential surface stability (as reflected by surface erosion and deposition) of the sand prior to crust establishment and to establish the monthly erodibility threshold below which biocrust establishment may take place. Since surface erodibility is a function of wind power but may be reduced by wet surfaces (Fécan et al., 1999; Reheis and Urban, 2011), both wind and rain variables will be analyzed.

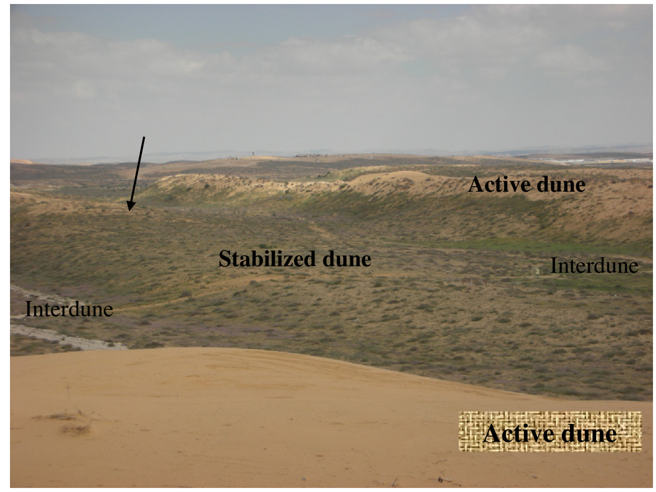

Fig. 1. General view of the research site. The arrow indicates the boundary between the stabilized and the active part of the dune. Photograph is taken from the northwest.

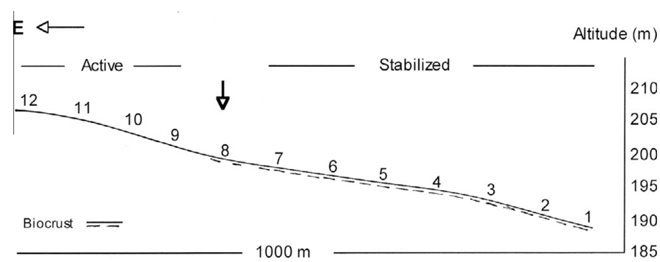

Fig. 2. A schematic drawing of the gradient along the dune. Arrow indicates the boundary between the stabilized and the active part of the dune.

2. Material and methods

2.1. The research site

The Nizzana research site (NRS) is part of the Hallamish dune field at the northwestern Negev Desert, Israel (34°23′E, 30°56′N). It is part of the easternmost terminus of the 13,000 km^2 northern Sinai Peninsula-northwestern Negev erg (Roskin et al., 2011). It consists of west-east trending longitudinal dunes, up to 20 m-high, separated by 50–200 m-wide interdunes. It is exposed to bi-directional winds, with medium–high speed southwesterly winter winds and low-medium speed northwesterly summer winds (Bitan and Rubin, 1991). Mean annual precipitation is 95 mm falling principally between November and March (Rosenan and Gilad, 1985). Mean annual temperature is 20 °C; it is 26 °C during the hottest month of July and 8 °C during the coldest month of January. Annual potential evaporation is ~2600 mm (Evenari, 1981).

Except for the crests of the high-elevation dunes, all sandy surfaces are covered by biocrusts. While relatively high-biomass crusts (mostly cyanobacterial with moss-dominated crust being confined to a narrow belt at the north-facing footslopes) characterize the north-facing slopes, a xeric cyanobacterial crust characterizes the interdunes, the south-facing slopes and the top of low-elevation dunes (Kidron et al., 2010). All dune crests have a low shrub cover of <3%.

The current research focuses on a stabilized dune that emerges from the interdune and eventually transitions into an active dune. While the dune crest is entirely covered by cyanobacterial crust in its western part, the dune crest becomes mobile with the increase in elevation toward the east (Fig. 1). For practical reasons and in order to distinguish this dune from adjacent dunes that have mobile crests throughout their entire length, this dune will be termed hereafter stabilized.

2.2. Methodology

For the evaluation of surface stability, 12 plots, 10 × 10 m and approximately 80 m apart, were demarcated during February 2010 along a transect that extends on one stabilized dune. The transect extends approximately 1 km eastward from the point in which the dune emerges from the interdune, 190 m above sea level, until reaching 212 m above sea level (Fig. 2). Measurements of the shrub and crust cover in 2 × 2 m quadrates within each plot were carried out following the establishment of the plot. Thereafter, a 4 × 4 m subplot was established in the center of each of the plots. The upper 3 cm of the surface of the subplot was removed and 6 erosion pins, 30 cm-long and 1 m apart, were inserted half way into the sand, i.e., 15 cm above ground in each subplot. Crust scalping, aiming to eliminate as much as possible biocrusts and inoculates, was repeated on a monthly basis when surface consolidation indicative of initial crust establishment was noted.

The change in pin heights was measured at the end of each month. Following each measurement, the pins were re-positioned at 15 cm above ground. Measurements took place between March 2012 and February 2012. For convenience, the twelve plots and subplots will be referred herein as stations.

Wind velocity and rain were measured at a nearby meteorological station 4.5 km south of NRS. Hourly wind velocity was used to calculate the drift potential (DP). The DP of all windstorms with a threshold wind velocity >6 m s^{-1} (which allows for sand translocation; see Fryberger, 1979) was calculated. Calculation was performed for the last 12 years (since 2001 when the meteorological station was established at the site), in accordance with Fryberger (1979):

$$\mathrm{DP} = \sum (U^2)(U - U_t)t$$

where DP = drift potential in vector units, VU; U = wind velocity in m s^{-1}; U_t = threshold velocity in m s^{-1} set at 6 m s^{-1}; t = the percent of time during which the threshold velocity is exceeded out of the total amount of hours during the year. For calculations, a single windstorm was defined as a storm during which the hiatus between threshold velocities does not exceed 12 h.

In order to gain insight into the long-term conditions at the site, rain and wind data that were collected at a nearby meteorological station since 2001 were also analyzed. To be corroborated with the field measurements DP was calculated from March 2001 to February 2012.

Table 1
Plot properties. Crust and plant cover were taken in 2 × 2 m quadrates ($N = 25$). Standard deviation in parenthesis.

Station number	Elevation (m)	Crust cover (%)	Shrub cover (%)
1	190	97.6 (1.3)	6.4 (16.8)
2	191	97.6 (1.5)	5.2 (12.3)
3	192	97.3 (1.2)	4.6 (9.6)
4	193	95.4 (2.8)	4.4 (10.5)
5	195	96.7 (1.4)	4.8 (9.4)
6	196	94.9 (2.9)	4.4 (10.7)
7	197	90.2 (3.3)	3.4 (8.1)
8	198	35.4 (8.2)	3.6 (8.6)
9	201	0.4 (1.4)	2.8 (6.8)
10	203	0.3 (1.1)	3.4 (8.3)
11	206	0	1.8 (6.3)
12	208	0	3.0 (7.2)

3. Results

Shrub cover at all stations was low, ⩽6% (Table 1). Crust cover was ⩾90% at station 1–7, practically absent from stations 9–12 and patchy with crust cover of ~35% at the transition zone, station 8 (Table 1).

Rain precipitation and drift potential (DP) that characterized the site in the last 12 years (2001–2012) are shown in Fig. 3. Both variables rain and DP showed high variability and did not exhibit a significant relation (not shown). Precipitation was substantially lower (66.4 mm; SD = 28.6) than the long-term mean of 95 mm (Rosenan and Gilad, 1985). It ranged between 30.4 and 110.1 mm, with seven out of the 12 years (2000/01; 2001/02, 2005/06, 2007/08, 2008/09, 2010/11, 2011/12) being drought years, defined as having <0.75 of the long-term mean precipitation (Jain et al., 2009; Pandey et al., 2010).

DP shows high monthly variability, with February having the highest DP, followed by March and January. Seasonally, the highest DP was exhibited during the winter with winter > spring ≫ fall > summer (Fig. 4). Average annual time duration during which $U_t > 6\ \mathrm{m\ s^{-1}}$ amounted to 439 h.

High annual and monthly variability characterized the rain distribution during field measurements (March 2010 and February 2012). While 2009/10 had above average precipitation (110.1 mm), 2010/11 and 2011/12 were both extreme drought years with 30.4 and 35.2 mm, respectively (Fig. 5). The rainiest months were March 2010, February and November 2011 and January and February 2012, each receiving 22.8, 19.3, 14.7, 8.8 and 8.1 mm, respectively.

The absolute monthly change in pin height of all stations is shown in Fig. 6. The values show a clear transition from the lower to the upper stations. Whereas stations 1–7 with ⩾90% crust cover had an average monthly change in pin height of 0.01–0.16 cm, stations 9–12, which represent non-crusted sites, had an average change in pin height of 1.2–1.5 cm. Station 8 with patchy crust cover had an intermediate value with an average absolute monthly change in pin height of 0.33 cm (Fig. 6). These results are supported by a cluster analysis that showed a clear distinction between stations 1–7 and 9–12. Interestingly, station 8, with its partially crusted surface, is more similar to the crusted stations 1–7. Stations 9–12 were subdivided into two groups, the relatively low-altitude stations 9 and 10 and the relatively high-altitude stations 11 and 12 (Fig. 7).

Seasonal drift potential and the average absolute change in pin height during the 24 months of measurements showed a similar trend with winter > spring > fall ≈ summer (Fig. 8). A good correlation with $r^2 = 0.73$ was obtained between the monthly DP and the average absolute change in pin height (Fig. 9a). The data also showed a good correlation with $r^2 = 0.85$ between altitude and the monthly absolute change in pin height along the transect (Fig. 9b).

4. Discussion

Dune mobility is primarily determined by wind power (Bagnold, 1941; Ash and Wasson, 1983). Yet, the effectiveness during which dune mobility takes place is largely determined by vegetation (Hesse and Simpson, 2006), biocrusts (McKenna Neuman et al., 1996) and moisture (Chepil, 1956; Gillette et al., 1980), with vegetation and crusts being especially vulnerable to anthropogenic disturbance (Gillette et al., 1980). High wind speeds (Mason et al., 2008), intense droughts (Miao et al., 2007), and anthropogenic disturbance of plants and crusts (Mason et al., 2008) are seen as possible causes for intense dune mobility.

Droughts affect moisture, vegetation, and biocrust establishment and cover. Knowledge regarding the conditions during which biocrust establishment may take place is of great importance. Both water and wind may be considered important variables for crust establishment. In NRS, positive significant relationships were found during 3 years of measurements between crust biomass

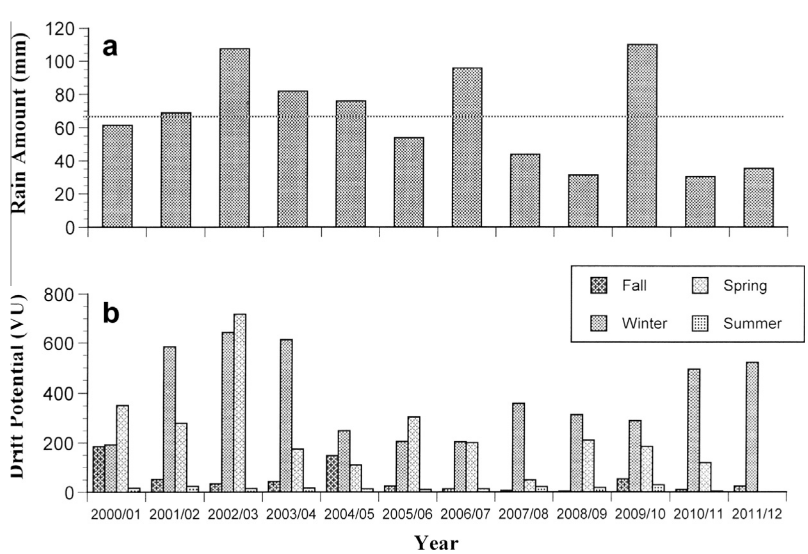

Fig. 3. Annual rain amount (with average indicated by a horizontal line) (a) and seasonal drift potential (DP) during the fall of 2000 to the winter of 2012 (b).

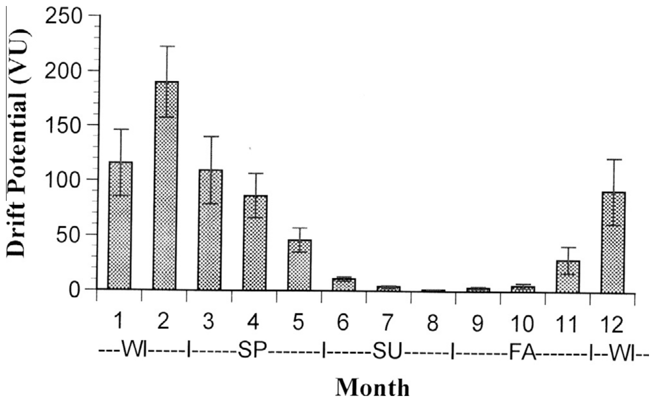

Fig. 4. Average monthly drift potential during March 2001 and February 2012. Note that drift potential follows the pattern winter (WI) > spring (SP) ≫ fall (FA) > summer (SU). Error bars represent ± one standard error.

(as reflected by its chlorophyll content) and the daytime surface wetness duration of its habitat, which acts as a surrogate for daytime crust activity (Kidron et al., 2009). Moreover, it was shown that under extended wetness duration a successional transition from cyanobacterial crusts to moss-dominated crust will take place (Kidron et al., 2010). High wind power on the other hand may impede crust establishment, as evidenced during wind tunnel experiments (Zhang et al., 2006), and reflected in the significant negative relations found between surface stability and crust cover (Kidron et al., 2009). As a result, arid regions with <50 mm and/or with very high wind velocities may not possess biocrusts (Verrecchia et al., 1995). Similarly, high wind velocities at the dune crest may impede crust establishment in NRS.

Drift potential showed a clear seasonal trend with winter > spring ≫ fall > summer during the 12 year analysis, similar to conditions described for the Mojave Desert (Bach et al., 1996; Reheis and Urban, 2011). Similar observations regarding the seasonality of dust emission in the Mojave Desert were also noted by King et al. (2011) who report substantial higher dust emission during winter. In agreement with previous reports (Bitan and Rubin, 1991), southwesterly winds were mainly responsible for the high DP during winter and spring, while low-DP northwesterly winds predominated during the summer and fall. The southwesterly winds are often accompanied by cold fronts, and subsequently by intense rainstorms (Enzel et al., 2008). An association between high-speed winds and intense rainstorms was also reported from northwestern US (Hunter et al., 1983).

After rain, the moist sand confers a greater shear strength on the dune surface (Chepil, 1956; Svasek and Terwindt, 1974; Skidmore, 1986; Muhs and Maat, 1993; Fécan et al., 1999; Hesse and Simpson, 2006), substantially reducing the likelihood of high surface erodibility. The periodical occurrence of wet surfaces (e.g. during January 2012, and February 2011 and 2012) and high wind speed may explain the fact that the correlation between DP and the change in pin height was not higher than 0.73. Analyses with U_t of 8, 10, 12 and 14 m s^{-1} (which corresponded to an average time duration of 123.4, 35.3, 7.2 and 1.0 h, respectively) did not improve the correlation (data not shown), implying that for a reliable prediction of surface stability based on the DP, a threshold of 6 m s^{-1} should be used, as was also previously suggested (Fryberger, 1979; Mason et al., 2008). Apparently, wet surfaces hindered erodibility during high wind speeds. In this regard, it is interesting to note that a wet surface following 35 mm of precipitation may also explain the fact that no visible erosion was observed following an exceptionally high-velocity windstorm of ~28 m s^{-1} (100 km h^{-1}) that took place during February 9th and 11th, 1992 (Kidron, 2001).

When compared to the average absolute change in pin height, a high correlation with altitude was obtained (r^2 = 0.85). Interestingly, although dune height increased gradually, an abrupt change in surface stability took place at a height of 9–10 m above the interdune (Fig. 9b). With absolute monthly change in pin height ranging between 0.01 and 0.16 cm at stations 1–7, it ranges

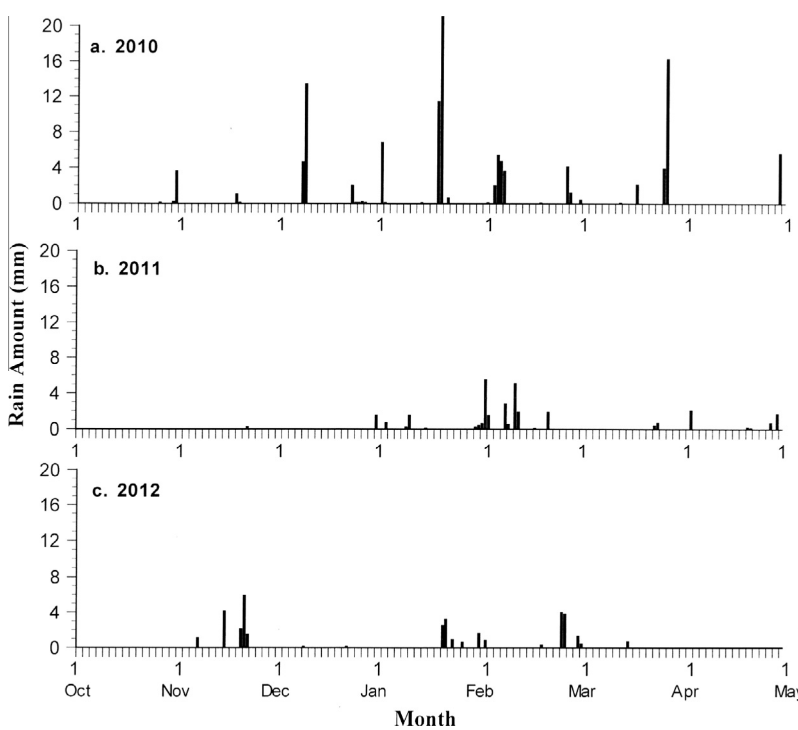

Fig. 5. The distribution of daily rain amounts during 2010–2012. While total precipitation was 110.1 mm for 2009/2010, it was 30.4 and 35.2 for 2010/11 and 2011/12, respectively. Ticks on the x-axis are spaced in two-day intervals.

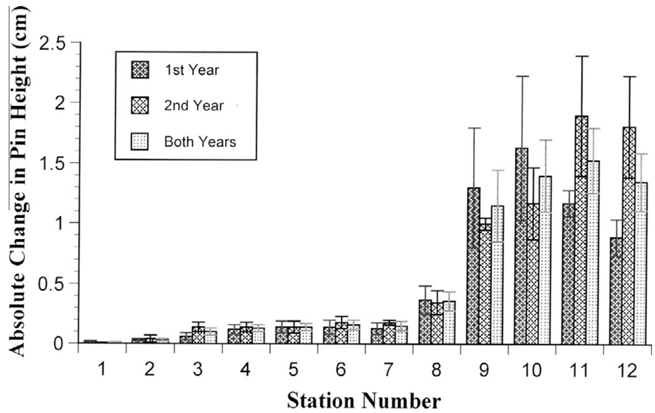

Fig. 6. Average monthly values of the absolute change in pin height at the 12 stations along the transect. Error bars represent ± one standard error.

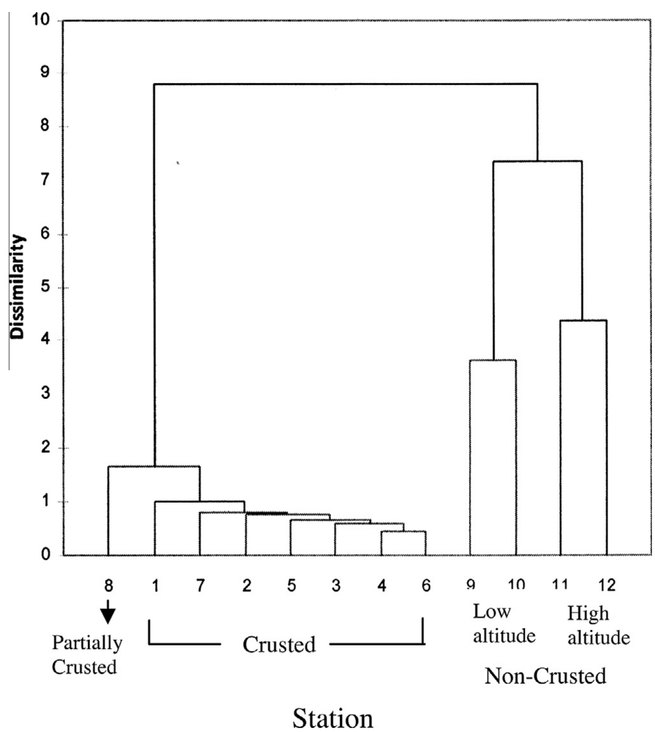

Fig. 7. A cluster analysis of all stations. Note the distinction between the crusted stations 1–7, partially crusted station 8, and the non-crusted low- and high-altitude stations 9–12.

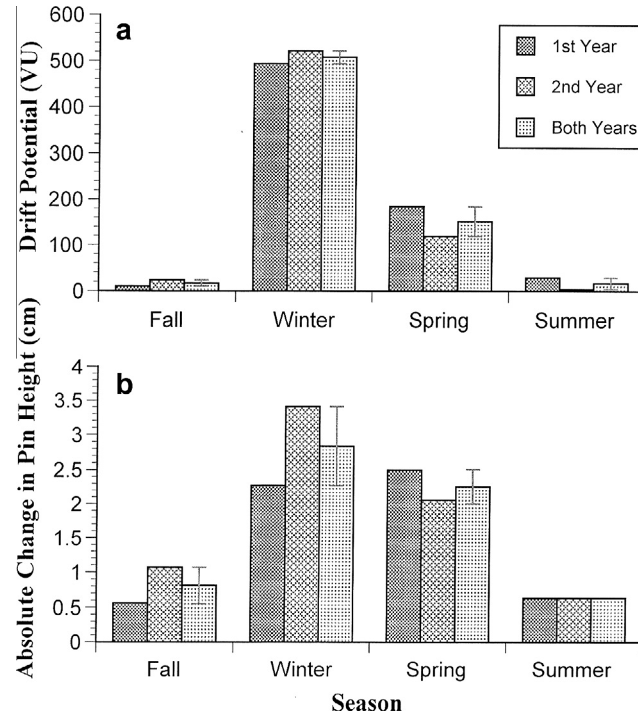

Fig. 8. Drift potential (a) and the average absolute change in pin height (b) during the fall, winter, spring and summer of both years of measurements. Error bars represent ± one standard error.

between 1.2 and 1.5 cm at stations 9–12 (Fig. 6). While stations 1–7 were located on formerly crusted surfaces, stations 9–12 lacked crusts. The confinement of a patchy crust cover to one station only (station 8) attests to a sharp boundary that exists between crusted and non-crusted surfaces. It implies that a very narrow window of surface stability may determine whether the surface will be crusted or not. In NRS, the threshold between continuous crust cover and surfaces that lack biocrusts under the current conditions corresponds to a monthly change in pin height of 0.33 cm. This takes place at an elevation of ~198 m, i.e., ~8 m above the interdune, as also evidenced at the northern limit of the dune field (34°22′E, 30°57′N). Lower and higher wind power may respectively increase or decrease the elevation threshold.

In this regard, field measurements that were taken by Arens et al. (1995) at foredunes in The Netherlands may be of relevance. Accordingly, while wind speed increased by 1.1 from the beach to an altitude of 6 m, it increased by 1.5 at an altitude of 10 m, with little effect thereafter when examined up to an altitude of 23 m. Accordingly, the most significant change in wind power took place between 6–10 m. With respect to wind transport (cubic relationship with wind velocity) it may result in a threefold increase in the sand-carrying capacity. Arens et al. (1995) findings are in agreement with the current findings pointing at a height of 8 m above the interdune as a transition zone between crusted and non-crusted surfaces. The substantially higher erodibility at stations 9–12 (11–18 m above the interdune) may reflect the substantial increase in the sand-carrying capacity of the wind, as well as increased erosive power.

While previous data (1992–1994) regarding the change in pin height (10.1–28.8 cm) were in agreement with the annual values currently recorded for the mobile dune sections (15.0–20.9 cm), the current values are by one order of magnitude higher than the annual values recorded for intact crusted surfaces. According to Kidron et al. (2009), annual change in pin height for the entirely crusted surfaces was 0.04–0.11 cm (in comparison to 1.1–1.3 cm during the current research), while being 0.24–0.28 cm (in comparison to 4.24–4.38 cm during the current research) for surfaces with a patchy crust cover. This may be primarily explained by the fact that while the values for 1992–1994 were monitored on intact (crusted or partially crusted) surfaces, all crusts were removed prior to the current measurements. As mentioned above, repeated scalping ensured that the measurements reflect non-crusted surfaces throughout the entire research period. Additionally, this may also be partially explained by the severe droughts and subsequently the dry surfaces that characterized the current research period.

The differences in the erodibility values between crusted and formerly crusted habitats point to the high efficiency in which crusted surfaces control wind erosion following their establishment. According to Kidron et al. (2000, 2009), wind erodibility at the crusted habitats of NRS is reduced by one order of magnitude

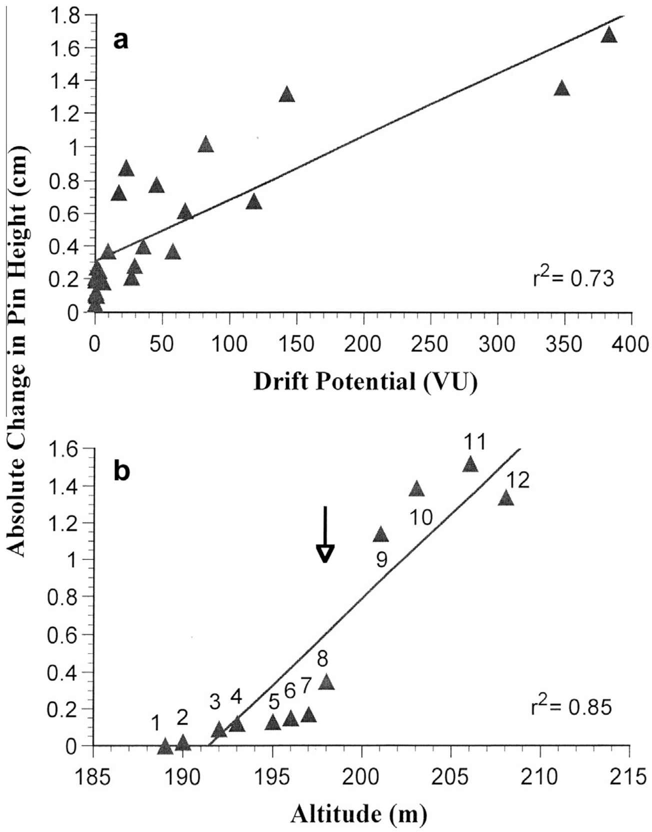

Fig. 9. The relationships between the monthly DP and the average absolute change in pin height at the 12 stations along the transect during the 24 months of sampling (a), and the relationship between altitude and the average monthly change in pin height at the different stations (b). Arrow marks the location of station 8 that exhibits an absolute change in rod height of 0.33 cm, reflecting the transition between the crusted (stabilized) and non-crusted (active) sections of the dune.

following crust establishment. The current data also suggest that under the current field conditions, habitats that experience a monthly absolute change in surface height of up to 0.16 cm are likely to experience crust establishment and subsequently total crust cover. Habitats that experience a monthly absolute change in surface height of ~0.33 cm are likely to experience partial crust establishment. Higher monthly absolute change in surface height will prevent a successful crust establishment.

With the cyanobacterial biocrusts at NRS reaching up to ~0.3 cm in thickness (Kidron et al., 2010), the current findings imply that as long as monthly sand deposition does not exceed 0.3 cm (i.e., the crust thickness), biocrusts are resilient to burial. This may be attributed to the motility capability of some of the dominant filamentous cyanobacteria such as *Microcoleus vaginatus*, which was found to respond to changes in light (Campbell, 1979) and water (Garcia-Pichel and Pringault, 2001). Since light penetration is limited to the first few millimeters (Garcia-Pichel, 2006), one may therefore conclude that light penetration does not only control the crust thickness but also marks the maximal sand thickness that is tolerated by the crust without being subjected to death following burial.

The findings highlight the potential role of biocrusts in the reduction of sand erodibility in the Sinai Peninsula under conditions in which grazing (and subsequently trampling) is restricted. With cell doubling time of the cyanobacteria of 70–80 h (Kidron et al., 2012), scalped surfaces were found to attain full recovery of their chlorophyll content within 6–7 years (Kidron et al., 2008). With high resilience to wind erosion (McKenna Neuman et al., 1996; Eldridge and Leys, 2003; Jia et al., 2008) following their unique crust structure (Mazor et al., 1996; Zhang et al., 2006), a positive feedback mechanism may thus take place. Within several years, newly formed crusts may substantially decrease surface erodibility and significantly reduce sand mobilization within the northern Sinai sand dunes.

The current findings highlight also the possible use of biocrusts as biomarkers for surface stability, as was also previously reported (Kidron et al., 2009). The data also imply that for the usage of cyanobacterial biocrusts as biomarkers of former surfaces (Svirčev et al., 2013), buried crusts may attest to monthly depositional rates >0.3 cm. This may take place in areas with sufficient wind power capable of covering already established biocrusts. This may also take place in crusted areas subjected to burial by sediment-laden runoff (Kidron, 2001).

Acknowledgements

We would like to thank H. Curtis Monger for fruitful conversation regarding this topic, Abraham Starinsky for his support, Isabella Grishkan for technical assistance and Carol A Kidron for the editing. We would also like to thank Mark Sweeney and another anonymous reviewer for their most valuable comments.

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