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Factors controlling the formation of coppice dunes (nebkhas) in the Negev Desert

Giora J. Kidron[1]* and Motti Zohar[2]
[1] Institute of Earth Sciences, The Hebrew University, Givat Ram Campus, Jerusalem, Israel
[2] Department of Geography, Hebrew University of Jerusalem, Mount Scopus Campus, Jerusalem, Israel

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*Correspondence to: Giora J. Kidron, Institute of Earth Sciences, The Hebrew University, Givat Ram Campus, Jerusalem 91904, Israel. E-mail: kidron@mail.huji.ac.il

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ABSTRACT: Due to their role in increasing fertility, coppice dunes (nebkhas) are regarded by many researchers as important contributors to aridland ecosystems. Yet, despite their frequent occurrence, little information exists regarding the rate and factors that control their formation. The goal of the current study is to examine the formation rate and factors that determine the establishment of coppice dunes in the Hallamish dune field in the western Negev Desert. The rate in which sand and fines, hereafter aeolian input (AI) was trapped and its particle size distribution (PSD) were examined by means of the solidification of 2 m × 2 m plots using surface stabilizers, and by the installation of three pairs of artificial shrubs (SH), three pairs of artificial trees (TR), and a pair of control (CT) plots. Measurements were annually conducted during June 2004 and June 2008, with monthly collection during June 2004 and May 2006. The PSD was compared to coppice dunes located on the fine-grained playa surface. AI was trapped at SH, while it was not trapped at TR and CT. The annual rate of AI accretion under the canopy was highly variable ranging between 1405 and 13 260 g m^{-2}, with a four-year average of 5676 g m^{-2}, i.e. 3.8 mm a^{-1}. It depended upon the wind power, with drift potential having a threshold velocity of $U_t > 10$ m s^{-1} yielding the higher correlations with the monthly AI ($r^2 = 0.59$–0.84). No significant relations were obtained between the monthly AI and shrub height. Sand saltation, suspension and creep are seen responsible for mound formation, which based on the current rates of sand accretion are relatively fast with a 60 cm-high coppice dune forming within ~150–160 years. The current data highlight the problematic design of some previous research using conventional traps and confining the measurements only to certain seasons. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: drift potential; dust; particle size distribution; sand; wind

Introduction

Protruding above their immediate environment, shrubs in arid and semi-arid regions may significantly modify the physical conditions under and around them. Shrubs have been reported to affect temperature regime and evaporation (Davenport, 1967; Barradas and Fanjul, 1986; Hennessy *et al.*, 1985; Kidron, 2009), as well as dew and fog condensation (Lloyd, 1961; Kidron *et al.*, 2002; Herrnstadt and Kidron, 2005). They have the capability of trapping aeolian input (AI), thus forming coppice dunes, termed also nebkhas (Tengberg, 1995; Dougill and Thomas, 2002).

While the term coppice dune or nebkha usually refers to under-canopy mounds of substantial height, low under-canopy mounds also abound in arid and semi-arid areas. Usually found in areas with lower aeolian activity, they are often termed macrophytic or phytogenic mounds (Zhang *et al.*, 2011; Du *et al.*, 2013). Whether referred to as coppice dunes (nebkhas) or phytogenic mounds, both types of mounds (termed hereafter under-canopy mounds, UCMs) are often considered to serve a positive role in the ecosystem. They were thought to play a central role in the formation of 'islands of fertility', i.e. habitats with enriched plants and biological activity (Schlesinger *et al.*, 1996; Kieft *et al.*, 1998).

UCMs have been reported in many parts of the world. While some attribute their formation to water erosion that takes place around the shrub (Rostagno and del Valle, 1988), or to sediment-laden runoff (Eldridge and Rosentreter, 2004), most UCMs are thought to result from dust-laden wind, which stem from up-wind erosion of sediments and their accumulation under the shrubs (Olson, 1958; Hesp, 1981; Nickling and Wolfe, 1994; Tengberg, 1995; Tengberg and Chen, 1998; Langford, 2000; Dougill and Thomas, 2002; Wang *et al.*, 2006, 2008; Seifert *et al.*, 2009; Li *et al.*, 2010; Zhang *et al.*, 2011; Quets *et al.*, 2013). Their formation was interpreted by some scholars to result from a combination of dust-laden wind coupled with water erosion (Gibbens *et al.*, 1983; El-Bana *et al.*, 2002), while others attribute their formation to a combination of dust-laden wind and sediment-laden runoff from upslope locations (Shachak and Lovett, 1998; Buis *et al.*, 2010). Splash by the raindrop impact was also suggested to play a role in their formation (Buis *et al.*, 2010).

UCMs were also reported from the Negev Desert, Israel. In a loessial ecosystem near Beer-Sheva (Sayeret Shaked with long-term precipitation of 200 mm), UCMs, 4–5 cm-high were thought to play an important role in enriching the ecosystem fertility (Shachak and Lovett; 1998; Buis *et al.*, 2010; Hoffman *et al.*, 2013). The formation of these low mounds was estimated to be extremely slow, ~250 years, being attributed to dust-laden wind, to deposition of eroded material by runoff and to the addition of *in situ* organic matter (Shachak and Lovett; 1998), or to a combination of water deposition (from the upslope sections) and erosion (around the shrub) (Buis *et al*., 2010).

UCMs are common in the Hallamish dune field in the western Negev Desert. Trending west–east, they abound at fine-grained sediments (termed playas) at the inderdunes of the Hallamish dune field. This is especially the case at the margins of the playas, which are characterized by scattered shrub growth, mainly *Anabasis articulata* or *Cornulaca monocantha*. As both species do not shed their leaves, we hypothesized that litter contribution to their formation may be marginal. We further hypothesized that AI is determined by plant architecture (whether shrub-like or tree-like shaped plants) and height while input is also controlled by season-dependent wind power. The aim of the current research is to evaluate these hypotheses.

Materials and Methods

The research site

The research was conducted at the Nizzana research site (NRS) in the Hallamish dune field, western Negev Desert, Israel (34° 23′E, 30°56′N). Long-term rain precipitation is 95 mm falling principally between November and April (Rosenan and Gilad, 1985). Average annual temperature is 20 °C; it is 26.5 °C during the hottest month of July and 11.8 °C during the coldest month of January. The wind regime is bi-seasonal with relatively strong south-western winds blowing during the winter and early spring and light to moderate north-western winds blowing during the remaining year (Bitan and Rubin, 1991). Annual potential evaporation is ~2600 mm (Evenari, 1981).

West–east longitudinal dunes characterize the dune field. They are comprised of up to 20 m-high dunes separated by 50 to 200 m-wide interdunes. The water-table is > 30 m in depth (E. Adar, personal communication, 1995), and the vegetation cover is sparse (10–20%). The interdunes have patches of fine-grained sediments, mainly comprised of silt. These silt-made loessial sediments, also termed playas, were laid down by the adjacent Nahal (arroyo) Nizzana by high floods during which the river bed was periodically blocked by the dunes (Kidron, 2001).

All middle and bottom slopes of the dunes are covered by biocrusts (also known as biological soil crusts), an assemblage of cyanobacteria, green algae, mosses, lichens, fungi and bacteria (in different proportion), which are only absent from the crests where wind speed is too high to permit crust establishment (Kidron and Zohar, 2014). Biocrusts also cover the sandy interdunes, while being absent from most of the playa surfaces, attributed to the short time during which the playas remain wet following rain (Kidron and Vonshak, 2012). Both surfaces, the sandy interdunes and the playa surfaces, may have UCMs (Figures 1a and 1b). Reaching up to 0.7 m, they have a typical

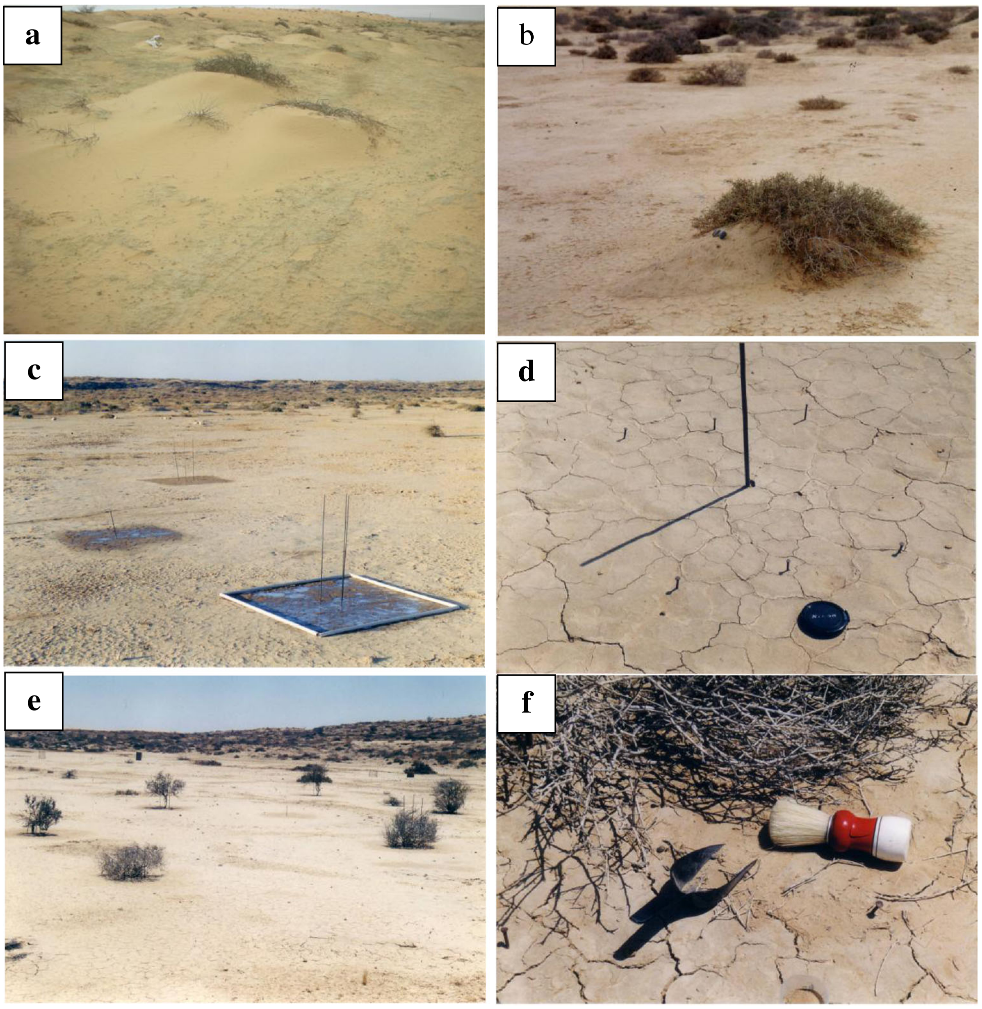

Figure 1. Coppice dunes on the sandy interdune (a), and at the margins of the playa surface (b), solidification of the plot surfaces (c), view of the control plot (d), a general view of the artificial plants (e), and AI collection using a brush (f). As can be noted, solidification did not change the crack density or microtopography. Note also the single and multiple stems that stand for trees and shrubs, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

west–east trending orientation with grain minerals extending beyond the shrub boundary at the eastern aspect (Figure 1b).

Methodology

A flat playa surface, with only scarce shrubs, was chosen for the study site. Most of the shrubs are characterized by 30 to 60 cm-high UCMs, with *Anabasis articulata* predominating along with *Retama raetam* and *Cornulaca monocantha* that inhabit the margins of the playa. Unlike species such as *Stipagrostis scoparia* and *Heliotropium digynum*, which are adapted to sand burial and/or erosion (Danin, 1996) and characterize the mobile dune crest (Kidron, 2015), all perennials at the playa surface are adapted to stable/semi-stable conditions.

Within a 50 m × 20 m area at the center of a playa (parallel to the east–west trending crest), seven pairs of plots, 2 m × 2 m each, were constructed, being therefore located at a similar distance from the immediate source of sand. Using water-soluble bonding material, known locally as BG bond (commonly used to consolidate cement), the upper surface was consolidated (Figure 1c). While six pairs were used for plant construction, one pair served as a control (Figure 1d). The material used for soil consolidation functions similarly to the addition of calcium carbonate ($CaCO_3$), which also acts to consolidate the surface (as verified by us following the addition of ~10% $CaCO_3$ to the surface, i.e. within the range of the amounts of $CaCO_3$ that characterize the playa; see Blume *et al*., 1995). Surface consolidation did not change crack density or the surface Z_0 (as can be noted in Figure 1d) and subsequently dust entrapment, while its effect on grain rebound is apparently within the range characterizing the playa surface, as could have been deduced by the shear strength values (using the TORVANE shear device, Durham Geo-Enterprise Inc., Stone Mountain, GA, USA) that fell within those of the natural surfaces. We assume that its effect may therefore be regarded as negligible. In addition, since solidification was limited to confined habitats only, it could not have affected the grain flux crossing the playa. And thus, due to the fact that all habitats were equally treated, and the original microrelief was not altered, we believe that the relative differences will remain unchanged even under slightly different surface compactness.

For plant construction, three 0.7 cm-diameter metal rods were used as scaffolds, and branches (with leaves) of the most common shrub type, *Cornulaca monocantha* were used to mimic plant architecture. Unlike *Anabasis articulata* that may readily loose its leaves following clipping, *C. monocantha* retains its leaves for years. At three of these pairs, artificial shrubs, SH (i.e. shrub-like plants with branches lying on the ground surface) were constructed while in the other three pairs, artificial trees, TR (i.e. tree-like plants with a central trunk with branches branching out only at 10–20 cm aboveground) were constructed (Figure 1e). Aiming to evaluate the impact of the shrub height upon accumulation (McKenna Neuman and Nickling, 1994; Gillies and Lancaster, 2013), each pair differed in plant height, being 30, 60 and 90 cm-high. A minimal distance of 8 m was maintained in between the plots to minimize mutual interactions.

The branches were tied to the rods in a manner that mimicked shrub-like and tree-like plants, while preventing their translocation during high-speed winds. Under each shrub and in the control plots, a 25 cm × 25 cm frame, was demarcated with four 10 cm-long nails that were inserted 9 cm into the ground at the four corners of the frame. These frames were demarcated at the main aspects (north, east, south and west) of the plants and at the under-canopy. Within the frames, a mobile wooden grid, 25 cm × 25 cm, with 5 cm × 5 cm squares each was placed at the end of each month, and the sediments from a randomly chosen square were collected in order to measure the amount that was accumulated within the square. Squares in which the collection took place were marked to avoid re-collection from the same square. Measurements at the squares were conducted monthly between June 2004 and May 2006, while additional measurements of all accumulated AI took place at all habitats during June of 2007 and 2008 (yielding annual rather than monthly rates of accumulation). Following the differences (although small) in the surface area of the plants, all AI are presented in g m^{-2}.

By collecting the AI directly from the surface rather than using the conventional traps, we avoided possible disturbance that may stem from the trap structure upon air flow and grain mobility. Contrary to conventional traps where grain settling does not facilitate re-saltation, suspension and creep, collection of the AI from the consolidated surface only introduces a negligible change, thus permitting a reliable comparison between all habitats. By creating this relatively firm 3 cm thick sole, the collection of the sand and dust (AI) was facilitated, using a fine brush (Figure 1f)

In addition, in order to assess the particle size distribution (PSD) of the natural mounds and their underlying playa surface, the sediments of four randomly chosen mounds and the underlying playa surface (to 10−20 cm-depth) were collected at 10 cm-intervals. The sediments (30−40 g each) were brought to the laboratory to measure soil organic carbon (SOC) and PSD.

All samples were oven-dried at 105 °C prior to the analysis. SOC was determined with potassium dichromate (Schollenberger, 1945). For the PSD, all samples were mixed with 0.5% of sodium hexametaphosphate and treated with ultrasonic waves for 10 minutes to ensure silt and clay separation. They were then wet-sieved through a 63 μm mesh, oven-dried at 105 °C until reaching a constant weight, and weighed for the calculation of the percent of fines, i.e. silt and clay (< 63 μm) within each sample.

Rain and wind data were obtained from a nearby meteorological station, 4 km south. As the station was established in the middle of a sand erg, characterized by similar shrub cover (~15%), it is assumed that the station may emulate the surface conditions at NRS. The data collected at the meteorological station included hourly rain and wind measurements. The data facilitated calculation of the drift potential (DP), in accordance with threshold wind velocities greater than 6 (considered the minimal velocity that permits sand translocation; see Fryberger, 1979), 8, 10 and 12 m s^{-1}. As was verified during numerous year-round field campaigns, 6 m s^{-1} was also the minimal velocity during which sand blasting took place at the NRS dune crests (Kidron and Zohar, 2014).

Calculation of DP has been executed for the last 12 years (since 2001 when the meteorological station was established at the site), in accordance with Fryberger (1979:

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

where DP is the drift potential in vector units, VU; U is the wind velocity in m s^{-1}; U_t is the threshold velocity in m s^{-1} set at 6, 8, 10 and 12 m s^{-1}; t is the percent of time during which the threshold velocity is exceeded out of the total amount of hours during the year.

To assess whether year, plant type and height determine AI, three-way analysis of variance (ANOVA) was executed. Differences were considered significant at $P < 0.05$.

Results

The distribution of fines and SOC of four randomly chosen 60–70 cm-high natural mounds and the underlying playa surface is shown in Figure 2. A clear difference is noted in the fine content between the mounds (at the upper ~60–70 cm) and the playa surface (> 60–70 cm). Whereas the mounds are comprised of sand with only ~10–20% of fines, high fine content of ≥ 60% characterized the playa surface. As far as SOC is concerned, both sediments showed great similarity. Both had a low SOC content of ≤ 0.12%.

Rain distribution during the study period is shown in Figure 3. Whereas precipitation during 2006/2007 (95.8 mm) was similar to the long-term mean precipitation (95 mm), all other years had below-average precipitation: 76.0, 53.9 and 43.8 mm for 2004/2005, 2005/2006 and 2007/2008, respectively. Only 1–2 rain events yielded daily precipitation of > 10 mm during each year of the study period, pointing to the relatively dry conditions that characterized the site.

Monthly accumulations for 2004/2005 and 2005/2006 are shown in Figure 4. No accumulation took place at the under-canopy of TR and at the control (CT). However, both years exhibited different patterns of accumulation at the SH, with 2005/2006 yielding substantially higher amounts than 2004/2005. This was verified by the three-way ANOVA. While AI yielded significant differences with plant type and year, it yielded non-significant differences with plant height (Table I). Accumulation also did not take place at the three of the four shrub aspects, north-facing, south-facing, and west-facing, while taking place at the east-facing aspect. Indeed, a good correlation (with r^2 = 0.68) was obtained between the amounts of AI obtained at the under-canopy and the eastern aspect of the shrubs (Figure 5).

The good correlation between the amounts of the AI of the under-canopy and east-facing aspect of the shrub also attested to the close link between both grain populations. Since the amount of fines may attest to possible differences in the source of the AI or to their mode of transportation, significant differences between the two habitats, as far as the fine content is concerned, may point to two distinct populations settling under

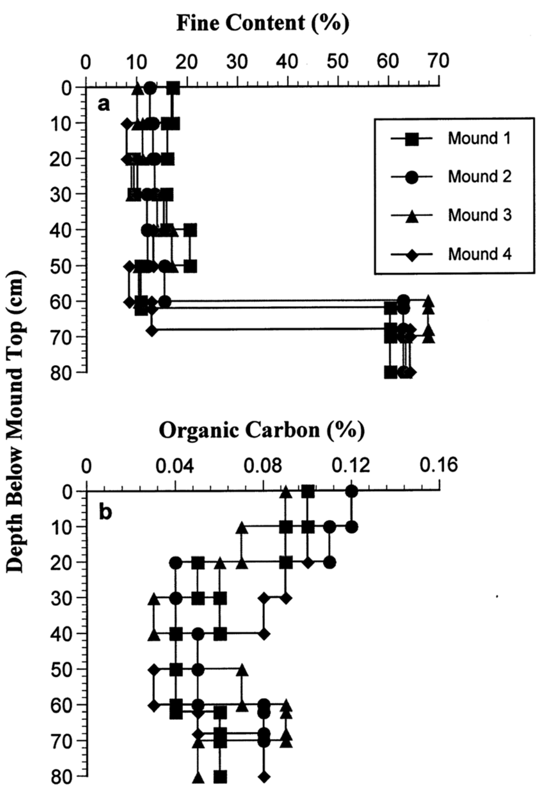

Figure 2. Distribution of fine content (a) and soil organic carbon (b) with depth of four under-canopy shrubs, ~60 cm-tall (Mounds 2, 3) and ~70 cm-tall (Mounds 1, 4).

and around the shrub. This however was not the case. The grain distribution of the under-canopy and the east-facing aspect of SH showed similar proportions. Similarly, similar proportions also characterized the PSD of the AI at SH (under-canopy and east-facing aspect), the mounds and the dune crests, with the parent material of the playa exhibiting substantially different proportions. Thus for instance, in comparison to a silt and clay content of 84.5% of the playa surface, silt and clay of all remaining surfaces ranged between 2.7 and 21.7% (Figure 6).

With $U_t > 12$ occurring only once during 2004/2005, analysis was confined to $U_t \geq 6, \geq 8$ and ≥ 10 m s^{-1}. DP with $U_t \geq 6, \geq 8$ and ≥ 10 m s^{-1} and the seasonal input at the under-canopy and the east-facing aspect of SHs for 2004/2005 and 2005/2006 are shown in Figure 7. Higher AI characterized the winter of 2004/2005 and spring 2005/2006 in agreement with the high DP of these seasons. As for the fall, while having a relatively high DP during 2004/2005, a low DP characterized the fall of 2005/2006. However, in both years the summer season exhibited the lowest DP. The data also show the close link between DP and AI, whether at the under-canopy or the east-facing aspect of SHs. Therefore, and in agreement with the high correlation of the monthly amount of the under-canopy and the east-facing aspect of SHs (as well as in the fine content), it was concluded that both populations concomitantly accumulated and could therefore be regarded as total AI.

Overall, when the seasonal drift potentials were compared with total AI, an increase in correlation from $U_t \geq 6$ m s^{-1} to $U_t \geq 10$ m s^{-1} was apparent (Figure 8), pointing to the fact that high wind power yields a better correlation with total AI. While no correlation could be obtained for DP with $U_t > 12$ m s^{-1} for 2004/2005 (since DP with $U_t > 12$ m s^{-1} was registered only once during February), it was 0.60 for 2005/2006 (not shown), i.e. substantially lower than 0.77–0.84 obtained for the lower values of U_t, thus pointing to the fact that DP with $U_t \geq 10$ m s^{-1} better reflected the total AI at the playa.

DPs and total AI, as measured during 2004–2008, are shown in Figure 9. DP with $U_t \geq 10$ m s^{-1} showed the higher correlation with total AI (with r^2= 0.52; not shown), similar to the conditions found for the seasonal analysis (Figure 6). Nevertheless the relationships between DP and the annual AI were not significant (not shown). Similarly to the results obtained for the monthly collection, non-significant relations also characterized the annual amount of AI and plant height (not shown).

Discussion

Any study pertaining to the effect of shrubs upon AI entails various difficulties. Among them, the subtle changes in wind regime caused by the shrub architecture, the small quantities of AI involved, and the variable ways in which grains are transported. Furthermore, traps tend to trap all grains, and thus the distinction between transient and non-transient grains (i.e. grains that settle and accumulate) is impossible to determine. Another source of error is shrub spacing and microtopography that may affect the wind regime, and hence the amount of AI trapped (Gillies and Lancaster, 2013). Animal refuge under shrubs and burrowing activity by rodents, often taking place under the shrub canopy (Bozinovic and Simonetti, 1992) are another source of disturbance. We attempted to address these drawbacks by the current technique of collection.

By establishing artificial shrubs at the playa surface, variability that stems from the shrub size and spacing as well as from animal disturbance and microtopography was avoided. Furthermore, following the fact that almost all AI was comprised of sand in contrast with the silty texture of the playa surface, differentiation between newly settled sand grains and the

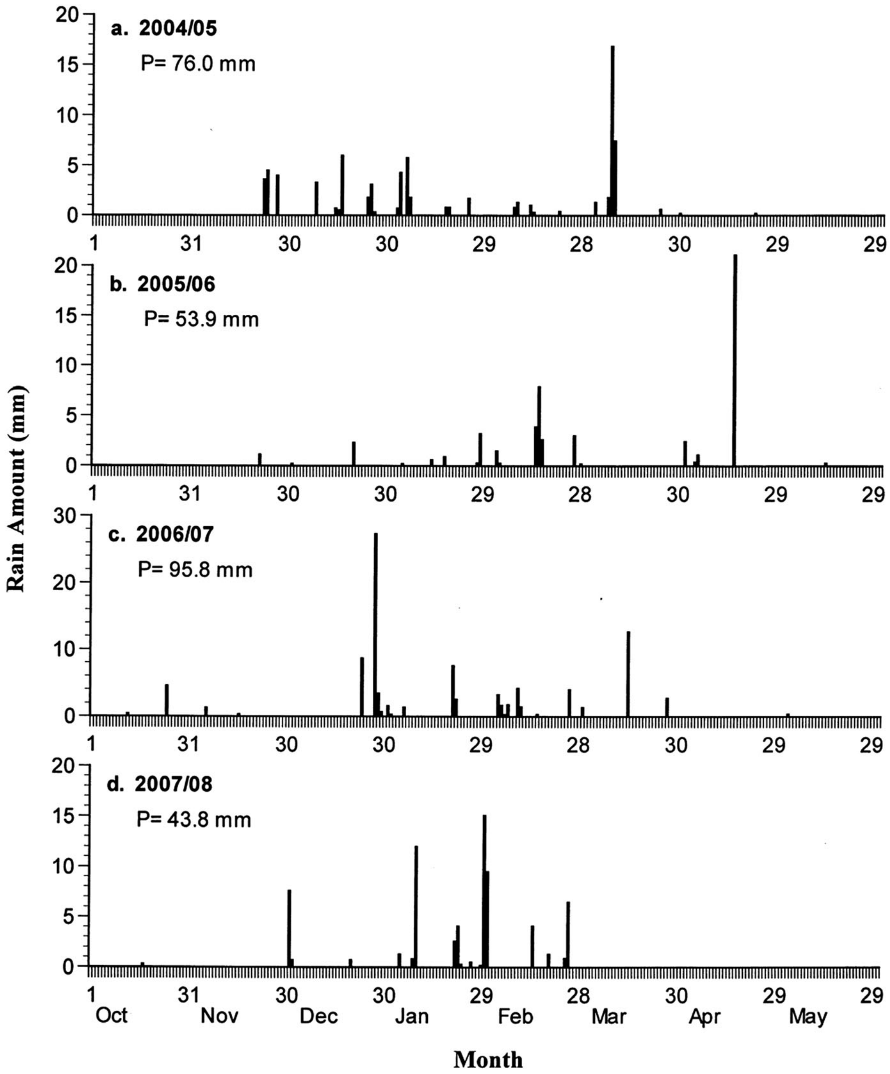

Figure 3. Daily rain events during 2004/2005 (a), 2005/2006 (b), 2006/2007 (c), and 2007/2008 (d).

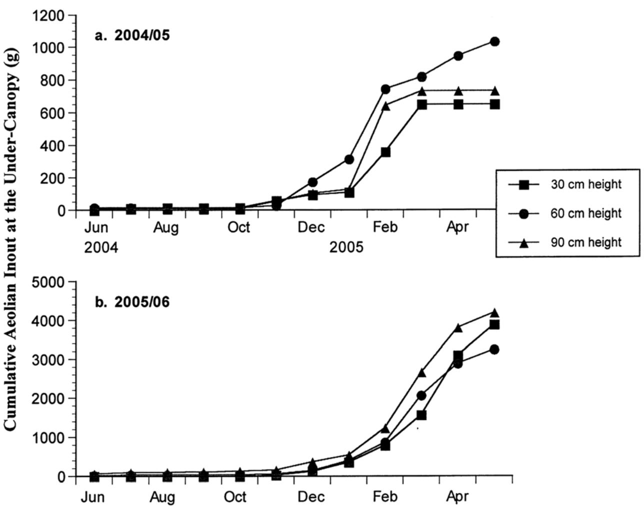

Figure 4. Cumulative aeolian input (AI) during 2004/2005 (a) and 2005/2006 (b) at the shrub-like 30, 60 and 90 cm-high plants. Note that no systematic increase in AI with shrub height was recorded.

substratum is relatively simple. By consolidating the surface, we guaranteed, as much as possible, that only newly settled grains will be collected and measured. Furthermore, the current method clearly differentiates between temporary and long-term grain settling, which may cause serious misinterpretations when conventional traps are employed.

While affecting the rate of accumulation, the climatic conditions had only a limited effect upon the spatial pattern of accumulation. No accumulation was recorded at the open, bare habitats (CT) and under tree-like shrubs (TR), regardless of season or year, in agreement with field observations in NRS that failed to detect mounds on bare habitats or under shrubs with a tree-like architecture such as *Thymelaea hirsute*. Our measurements also showed that while ~90% of the sand was trapped under the shrub canopy, the remaining ~10% was deposited, concomitantly, at the east-facing aspect of the shrub, again, in agreement with the current situation in the field in which the mound extends beyond the shrub limits only at the east-facing aspect.

Sand made up approximately 80–85% of the AI content, in agreement with the PSD of the sand dunes (> 90%), implying that sand dunes are the main source of grains. As a result of a channeling effect at the interdune, a predominantly western resultant drift potential (RDP) was registered. Moreover, similar to other dry playas characterized by a compacted and hard surface (Reynolds *et al.*, 2007), no wind erosion was noted at the playa surfaces during windstorms. In contrast to playas in the south-western United States, which may be characterized by unconsolidated surface layer and may therefore serve as a dust source (Reynolds *et al.*, 2007; Lee *et al.*, 2009; Sweeney *et al.*, 2011), no wind scouring was ever observed at the playa surfaces, not even during high-velocity windstorms, a phenomenon that is ascribed to the compacted surface of the playas. This was also verified by

Table I. A three-way ANOVA for aeolian input (AI) in relation to year, type of plant (shrub-like and tree-like) and height (30, 60 and 90 cm).

Source of variation	SS	df	*F*	*P*-Value
Year	4660010.9	1	14.377	0.000
Plant type	6557111.9	1	20.229	0.000
Height	45215.6	2	0.070	0.933
Year × plant type	4660010.9	1	14.377	0.000
Year × height	80050.1	2	0.123	0.884
Plant type × height	45215.6	2	0.070	0.933
Year × plant type × height	80050.1	2	0.123	0.884
Error	42786530.5	132		
Total	65471307.6	144		

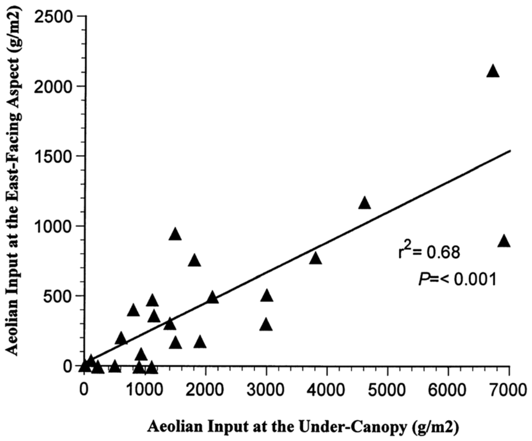

Figure 5. The relations between under-canopy and east-facing aeolian input.

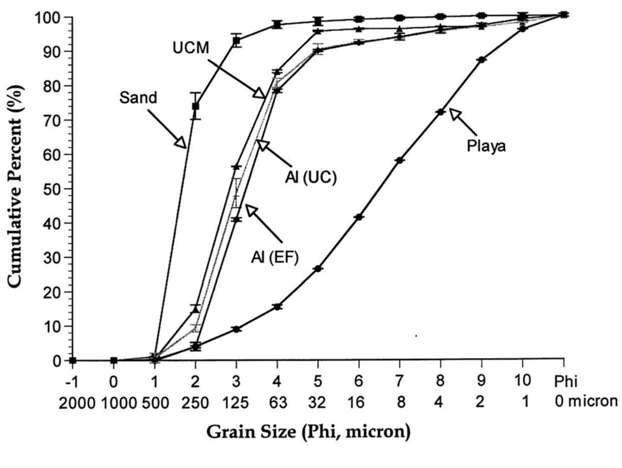

Figure 6. Particle-size distribution of the aeolian input (AI) under the plant canopy (UC) and at its east-facing aspect (EF) of the under-canopy mounds (UCMs), the dune sand (taken from the mobile crest) and the playa surface.

measurements using erosion pins (Kidron, unpublished). Alternatively, the playa's facilitation of runoff (Kidron, 2014) resulted in water erosion. Indeed, some of the > 40 cm mounds at the playa surfaces were characterized by 3–5 cm-high fine-grained pedestals that underlie the mounds, attesting to surface degradation during the time that lapsed since mound establishment. Obviously, as was clearly observed in the field and in line with Figure 2 which shows two very distinct PSD that characterize the mounds (~0–60 cm) in comparison to the underlying playa surfaces (> 60 cm), nebkha formation by water erosion at our site, as reported by Rostagno and del Valle (1988) was ruled out.

While not affecting the spatial pattern of accumulation, climatic conditions affected the accumulation rate. During the current research, high inter-annual variability characterized the rain precipitation, from 43.8 mm (2007/2008) to 95.8 mm (2005/2006), with three out of the four research years being characterized by below-average precipitation. When the DP with $U_t \geq 6$ m s^{-1} was analyzed, similar DP values characterized the years 2004/2005 and 2005/2006 (with DP of ~520 to 550 VU) and 2006/2007 and 2007/2008 (with DP of ~430 VU). More pronounced differences were however received once the DP values with $U_t \geq 10$ m s^{-1} were calculated. Whereas 2004/2005 and 2008/2007 had a DP of 83 to 111 VU, 2005/2006 and 2007/2008 had a DP of 210 to 215 VU. Over 90% of the winds blew from the west, in agreement with long-term data (Bitan and Rubin, 1996).

The relations between total AI and the monthly DP (with U_t > 10 m s^{-1}) showed good correlations with r^2 = 0.59–0.84. Although higher shrubs are expected to intercept higher amounts of AI as a result of the larger air volume that they occupy and their lower porosity (Grant and Nickling, 1998; Gillies and Lancaster, 2013), no significant correlation was obtained between AI and shrub height as verified by the statistical analysis, in disagreement with our initial hypothesis. This may be accounted for by the important role played by sand creep, which may mask the portion of AI carried by the air mass.

The high variability in the annual DP, on the one hand, and the high correlation between the annual DP (with $U_t \geq 10$ m s^{-1}) and total AI, on the other hand, attests to the high variability of the annual input at the site in accordance with wind power. In this regard, it is interesting to note that higher correlations were obtained between AI and DP with $U_t \geq 6$ m s^{-1} on the dune crest (Kidron and Zohar, 2014), in agreement with previous publications (Fryberger, 1979; Forman *et al.*, 2009; Singhvi *et al.*, 2010). However, as also verified during windstorms, while wind velocities with $U_t \geq 6$ m s^{-1} were sufficiently powerful to translocate sand at the mobile dune crest, they did not suffice to translocate sand at the interdune. Apparently, higher velocities are necessary to effectively translocate sand at the low-lying interdunes.

However, apart from the DP, wind erodibility is also dependent on surface moisture. Since rain and wind storms in the Negev are often linked (Enzel *et al.*, 2008), surface moistening by rain may drastically decrease surface erodibility (Kidron and Zohar, 2014), and subsequently the supply of sand grains to the playa from the adjacent dune crests. This may explain the outliers in Figure 8a that show months with relatively high DPs (with DP > 100 VU at U_t > 6 m s^{-1}, such as those recorded during November 2004 and January and February 2005) yielding high (during February 2005) and low (during November 2004 and January 2005) AI, explained by the relatively low precipitation during February 2005 (with 3.9 mm) in comparison to higher precipitation of 12.1 mm and 14.2 mm during November 2004 and January 2005, respectively. The effect of surface moistness was also reflected in the annual records, with drought years exhibiting substantially higher AI. While no biocrust rupture was noted, a combination of high-wind velocities and dry surfaces during the winter of a drought year will result in high erodibility, as also previously reported (Kidron and Zohar, 2014). And thus, albeit similar values of DPs during the four-year research, a substantially higher amount of AI was recorded during the extreme drought year of 2007/2008 (43.8 mm).

As evidenced in the field, both saltation and creep (rolling and sliding) were mainly responsible for AI accumulation under the shrubs. Under-canopy branches that were touching the ground tended to accumulate large amounts of grains, interpreted to result from rolling and sliding. However, while serving to impede further sliding and rolling (as evidenced in all shrub-like plants), low-lying branches cannot explain mound

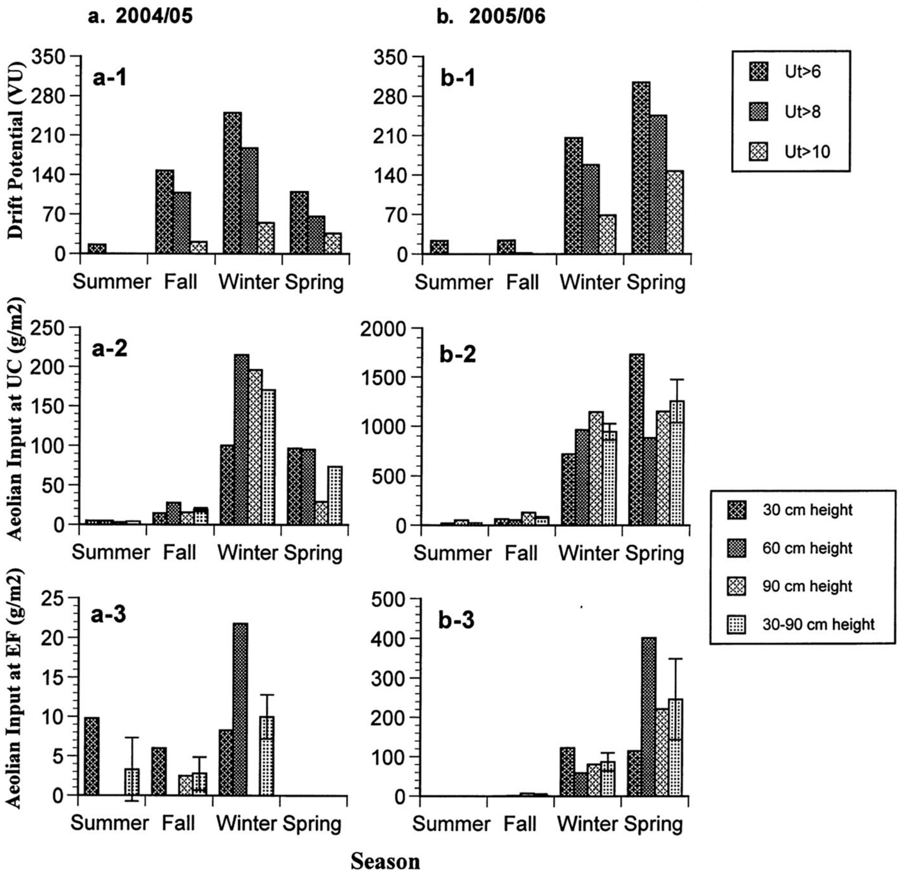

Figure 7. Drift potentials, DP (with $U_t \geq 6$, $U_t \geq 8$ and $U_t \geq 10$ m s^{-1}), and aeolian input at the under-canopy and east-facing aspect of the shrub-like plants during the summer, fall, winter and spring of 2004/2005 (a) and 2005/2006 (b). Bars represent one standard error.

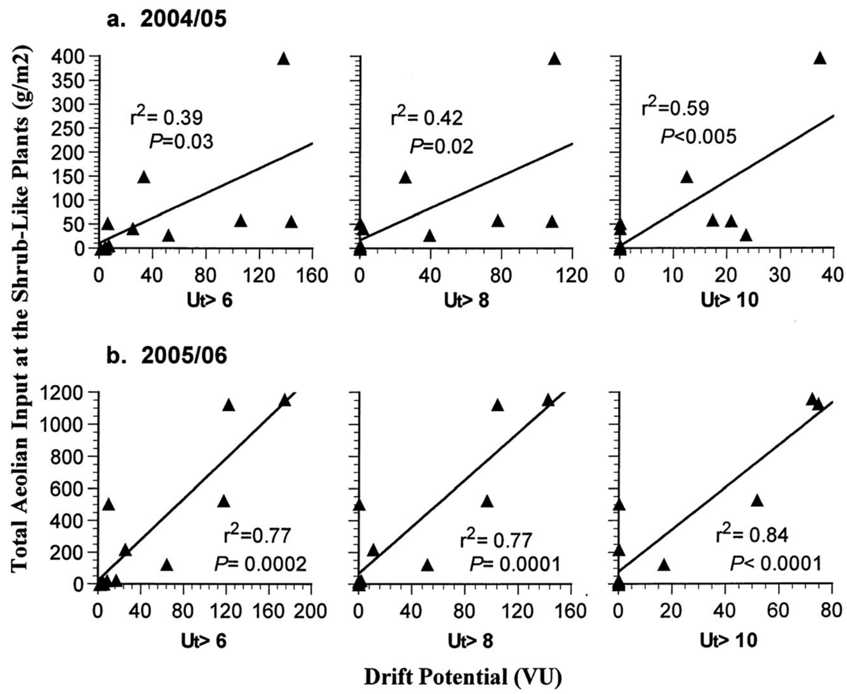

Figure 8. The relations between DP with $U_t \geq 6$, $U_t \geq 8$ and $U_t \geq 10$ m s^{-1}, and the average total monthly accumulation of the aeolian input (AI) of 30, 60, 90 and 30–90 cm-high shrub-like plants during 2004/2005 (a) and 2005/2006 (b).

growth with height, i.e. the vertical accumulation of grains. Mound growth necessitates therefore sand supply by air mass, mainly attributed to saltation.

Regarded as the main mechanism for dune formation (Bagnold, 1941), saltation is described as sand grains propelled by wind in a succession of hops (Ho *et al.*, 2012). Once lifted, a grain that strikes the surface imparts momentum to stationary grains which may result not only in the rebound of the original grain but also in the ejection of one or more stationary grains into the air stream. Once initiated, this will take place at lower shear velocities than those required to entrain the stationary grains by direct fluid pressure (Nickling, 1988). Due to these

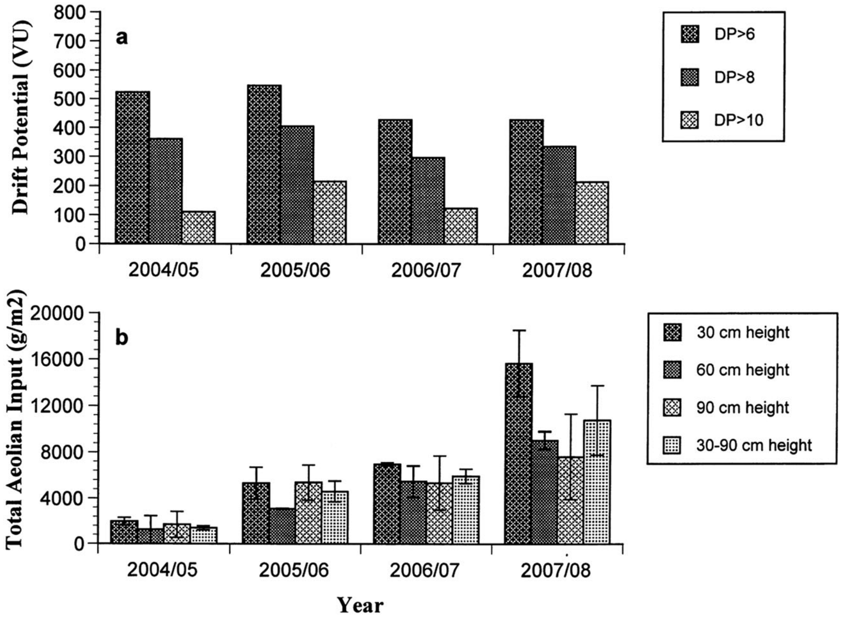

Figure 9. Drift potential, DP (with $U_t \geq 6$, $U_t \geq 8$ and $U_t \geq 10$ m s^{-1}) (a), and the average total annual accumulation of the aeolian input (AI) during 2004–2008 (b). Bars represent one SE.

interrelations, lower shear velocities will be required for effective saltation to take place over a sandy surface. This may result in turn in a relatively fast formation of UCMs at the dune crests or sandy interdunes, as observed in the field following high-speed windstorms, and reported in the literature (Gile, 1966; Nickling and Wolfe, 1994). Nevertheless, whereas the high supply of sand may explain the relatively fast formation of UCMs at the sandy surface, a relatively fast formation of the UCMs at the playa surfaces may also take place, accounted for by the higher heights and higher speeds of the saltating grains over the hard playa surface (Dong *et al.*, 2003).

It follows that during high-velocity winds, sand grains that mainly originate from the crests of the longitudinal dunes, are transported to the interdune. Whereas limited transportation may take place at $U_t > 6$ m s^{-1}, substantial transportation to larger distances will take place at $U_t > 10$ m s^{-1}. Moreover, while saltation was not noted at the relatively sheltered and low-altitude interdune at U_t ~6 m s^{-1}, it took place at $U_t >$ 10 m s^{-1}, thus explaining the better correlations obtained between AI and DP with $U_t > 10$ m s^{-1}.

While thought to only make a very limited contribution (Arens *et al.*, 2002; Li and Guo, 2008), the role of suspension in the UCM formation cannot be ruled out. This may stem from the short distances between the source of the sand (the dune crests) and the UCMSs. It is also supported by the relatively high proportion of the fine sand in the UCMs (Figure 6), typical for suspension (Bagnold, 1941). Suspension is therefore also suggested as one possible mechanism for the formation of the UCMs.

With saltation, suspension, and creep being apparently responsible for grain accumulation at SH, the absence of accumulated sand at CT and TR is expected. Even if saltating or suspended grains are trapped by the branches of TR and forced to settle, wind power under the TR is apparently sufficiently strong to evacuate these grains from under the TR (as well as from the CT). Alternatively, once protected from the predominant high-speed western winds at the SH, sand particles are trapped not only at the under-canopy of the shrub but also at the leeside (i.e. at the east-facing aspect), thus corresponding to sand accumulation models behind obstacles (Wolfe and Nickling, 1993).

The above-mentioned findings are in agreement with the PSD of the adjacent UCMs. There too, mineral grains accumulated beyond the canopy limit of the east-facing aspect, while not existing in all other aspects. Furthermore, as was the case under the SH, the grain size distribution was primarily sand, as is also the case for the UCMs at the dune summit. Thus, although located on fine-grained sediments (playa), the coppice dunes and the grain size accumulating under the shrubs were primarily sand size. Sand (which is mainly transported from the crests of the longitudinal dunes) with some enrichment of aeolian dust (which may explain the 15–20% fine content at the mounds in comparison to ~5–10% of the dune sand) are therefore regarded as the source material for the formation of the coppice dunes in NRS.

Since sand accumulation is shelter-dependent, burial of the shrubs by sand is not expected. The current research thus indicates that under the current wind regime, climate conditions and sand supply, a 10 cm high UCM will be formed during ~25 years. Consequently, assuming similar conditions, estimated age of the 60 cm-high coppice dunes in the interdunal playas of NRS is ~150–160 years. This is substantially shorter than previously reported rates from the Negev (~250 years for 5 cm-high mounds; see Shachak and Lovett, 1998). This is explained by the proximity of the sand source to the mounds at NRS, and by the fact that estimates by these authors were solely based on summer monitoring, which is far from representing the effective wind regime. Indeed, if only summer measurements would have been conducted, the estimated age of the 60 cm-high coppice dunes in the playas of NRS would have been ~13 000 years, i.e. almost two orders of magnitude longer.

The current research strongly supports Dougill and Thomas (2002 findings regarding the formation of UCMs in South Africa and Botswana, and is in agreement with other findings that reported sand enrichment at the under canopies (Gile, 1966; Wood *et al.*, 1978; Nickling and Wolfe, 1994). Situated at the playa surfaces, wind erosion of the playa surface was excluded, while water erosion was minimal and therefore negligible for the formation of the UCMs in NRS. While wind scouring takes place at the dune crests (in agreement with other reports; see Li *et al.*, 2010; Kröpfl *et al.*, 2013), the strong cohesion of the surface does not facilitate wind erosion at the playa. The sandy texture of the mounds cannot also be explained by water erosion at the shrub vicinity or by deposition of sediments by runoff, as previously suggested for the central Negev (Shachak and Lovett, 1998).

With seasonality playing an important role in the formation of UCMs, and with the importance of saltation, suspension and creep (sliding and rolling) in grain translocation, the use of conventional traps such as Petri dishes and the confinement of the measurements to the summer months as previously suggested (Shachak and Lovett, 1998) is not recommended. With dust-laden winds in the Negev taking place principally in the winter and spring, estimation of the age of the mounds based on measurements carried out only during the wind-calmest season of the summer inevitably results in overestimation of the mound age.

With low SOC and high sand content of > 80 to 90%, proliferation of annuals at the UCMs, as reported for the Hallamish dune field (Holzapfel *et al.*, 2006), should be principally attributed to amelioration of the abiotic conditions. Following shading, substantially lower temperatures and hence evaporation characterized the under-canopy habitat of NRS (Kidron, 2009), which results in turn in substantially higher moisture content, lasting for up to one month longer at the upper 0–30 cm soil profile (Kidron, 2010). This may facilitate in turn extensive cover of annual plants (Brooker and Callaghan, 1998; Holzapfel and Mahall, 1999), high biomass biocrusts (Kidron and Vonshak, 2012), and extensive microbial activity (Herman *et al.*, 1995; Berg and Steinberger, 2008), all of which benefit from and contribute to the under-canopy habitat.

Summary and Conclusions

The research evaluates the mechanisms and estimates the rate during which coppice dunes (termed here as under-canopy mounds, UCMs) are formed. The approach adopted included shrub-like and tree-like construction on solidified surfaces and the monthly and annual measurements of the accumulated AI. The findings indicate that (a) no accumulation took place at the tree-like shrubs and the control while taking place at the shrub-like plants, (b) net accumulation at the shrub-like plant was confined to two habitats: the under-canopy and the east-facing aspect, (c) accumulation rate depends upon sand saltation, suspension and creep with sand comprising > 80% of the grain minerals, in agreement with the existing texture of the UCMs, (d) a close link was found between seasonal DP and AI, with winter and spring yielding the highest AI, (e) a good correlation was found between annual DP and AI with DP based on $U_t \geq 10$ m s^{-1} yielding higher correlation than that based on $U_t \geq 6$ m s^{-1}, (f) non-significant relations were found between AI and shrub height, partially explained by the fact that grain translocation by creep acts to mask the amount reached through the air mass, (g) mound formation is fast with a 10 cm-high coppice dune being estimated to form within ~25 years. We maintain that for the assessment of AI accumulation some of the classical methods (traps) and the confinement of the measurements to certain seasons only are doomed to fail as they may lead to gross errors. As the amount of SOC under the mounds is low, annual plant proliferation may primarily stem from the amelioration of the abiotic conditions, as previously suggested (Kidron, 2010).

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