Sand dunes mobility and stability in relation to climate

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Abstract

Sand dunes form an important and unique system that can be mobile or fixed by vegetation. The common mobility indices of sand dunes, which are related to the wind and the amount of precipitation and potential evaporation, do not work in many dune fields around the world. The reasons for that lie in the singular physical characteristics of the sandy soil. Sand has high hydraulic conductivity causing a high rate of infiltration of rain water to the groundwater. Sand particles lack cohesion and that makes wind erosion the main limiting factor for vegetation. Hence, wind power, manifested by the drift potential (DP), is a good index for the limiting factor of plants on sand. The physical - biological interaction is further developed by hysteresis, which shows that a dune can become vegetated when the wind power is sufficiently low. Once vegetated, a much higher wind stress is needed to destroy the vegetation and re-activate the dunes.

Key words:
sand dunes, climate change, wind power, dune mobility, dune stability, mobility index

1 Introduction

Sand dunes are known to be: (*i*) free of vegetation and active (*ii*) partly vegetated and active (*iii*) fully vegetated and fixed. It is customary to conclude that the stabilized sand dunes of the world indicate mobility in the past, probably under more xeric climate regimes. Since the seminal work of Sarenthein [1] that attributed the vast active dune coverage during the last glacial

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maxima to drier climates, many geologists and geomorphologists relate the mobility of sand dunes during the Upper Quaternary to an increase in aridity while stability by vegetation occurs during wet phases (see e.g. [2–5]).

It is obvious that all fixed dunes were active in the past and became stabilized when their climate changed. Most scientists refer to climate change as a change in rainfall and temperature, which are the two important climate elements that affect vegetation growth [6]. The concept of active dunes formation under arid conditions and natural fixation during wet periods is based on the known interaction of temperature with precipitation as an important determinant of the average annual net primary biomass production [7]. For this reason, it is expected that sand dunes in hot deserts would be devoid of vegetation and active, while the dunes along the coasts of humid areas would be vegetated and stabilized. However, there are many examples of active sand dunes in humid areas [8,9] and stabilized dunes in arid areas [10]. The aim of this paper is to explain the phenomenon of active sand dunes in humid areas and stabilized sand in arid climates and to explicate the effect of climate change on the mobility and stability of sand dunes.

2 Mobility indices of sand dunes

Several wind erosion or sand mobility indices have been developed for various parts of the world [11–13]. All of them are based on two factors that increase or decrease dune mobility. The first one deals with the degree of windiness (W - expressed as the average annual wind velocity to the third or fourth power or as the annual percentage of days experiencing winds above the threshold velocity for sand movement). Most dunes will be mobilized if windiness is increased. The second factor that favors vegetation growth is the ratio between the annual average precipitation (P) and the annual potential evaporation (PET), also known as the rain efficiency.

Wasson [14] introduced a comparable version of sand mobility equation for Australia, which he sees as a better one with a more readily evaluated relationship.

$$M = 0.21\left(0.13W + \ln\frac{PET}{P}\right)\,. \tag{1}$$

Based on equation (1) Lancaster [15] developed a simpler equation that is based on the same idea:

$$M = \frac{W}{P/PET}\,. \tag{2}$$

The M-index of equation (2) was calibrated by Lancaster [15] who found the critical values of M for Southern Africa to be above 200 for fully active dunes with no vegetation, and below 50 for inactive vegetated dunes. This M-index (2) is widely used by geologists and geomorphologists to determine whether sand dunes would be active or fixed as well as the expected effect of climate change on dune fields [16–22]. Muhs [23] found a better pertinence between the degree of dune activity and the P/PET values for the Great Plains sand dunes, while W is of lesser importance.

3 The unique physical properties of sand as a soil and its effect on vegetation cover

Dune sand is known as inert soil devoid of any positive characteristics for flora. This is due to: (a) the relatively coarse particles and the big pore spaces which result in a low amount of available water to plants. (b) The high rate of permeability and leaching resulting in the washing away of nutrient elements necessary for plant growth [24]. (c) The lack of cohesion between the grain particles resulting in easy erodibility of the sand. Sandy soils have the lowest threshold velocity for aeolian erosion of all known soils [25].

The above singularity of the dune sand can explain why rainfall or the rain efficiency (P/PET) is not as decisive a factor in dune stabilization and mobilization as it is customary to believe. The permeability of dune sand is 2,500 times higher than that of soil composed of smaller particles of silt and clay [26]. Hence, most of the rain in humid areas will infiltrate to the ground water and the available moisture will be at or close to the low field capacity.

The M-index (Eq. (2)) refers to the average rainfall, average potential evaporation and the percentage of days during the year with sand moving winds (W). According to the aforementioned, the first two factors are not significant on sand dunes because of the sand texture. Wind is the only limiting factor for vegetation on sand dunes, where there is no human pressure. However, the M-index refers neither to the wind magnitude nor to the wind directionality.

A better index of wind erosion is the drift potential (DP) of the wind [27] which is based on the sand erosion (q) equation:

$$DP = \sum q = \frac{U^2(U - U_t)}{100} t \,, \tag{3}$$

where U is the wind velocity (in knots), measured at a height of 10 m, Ut is the threshold wind velocity (=12 knots) and t is equal to W in Eq. (2), i.e., the time the wind blew above the threshold velocity (in percent). The division by

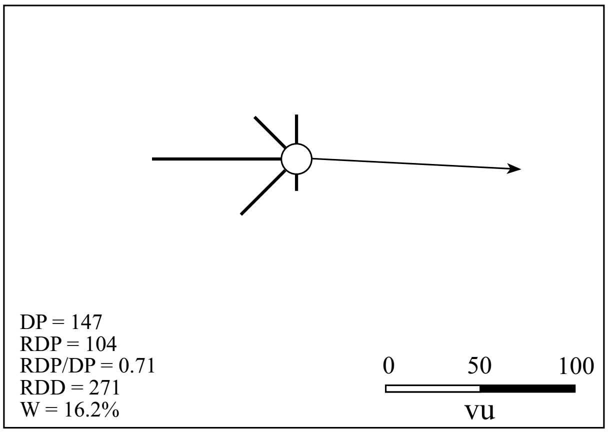

Fig. 1. Average annual sand rose for the coastal dunes south of Tel Aviv, Israel. The DP vectors are proportional in length to the potential sand transport in the direction toward the central point. The net potential trend of the DP vectors (RDP) is shown by the arrow in the direction of the resultant drift direction (RDD).

100 is for reducing the result to a smaller number. q is calculated separately for each wind direction, which is experiencing wind above the threshold velocity (U_t) and its value is known as a vector unit. All vector units from all the wind directions form a sand rose (Fig. 1). DP, the total annual q for all wind directions, is a parameter of the potential maximum amount of sand that could be eroded by the wind during a year for all wind directions. Hence, DP is a measure of the potential wind power in a sandy area.

The vector units from different directions can be resolved into a single resultant known as the resultant drift potential (RDP). The index of the directional variability of the wind is the ratio of the resultant drift potential to the drift potential of the wind (RDP/DP). Values of RDP/DP close to one indicate narrow unidirectional drift potential, and values close to zero indicate wide multidirectional drift potential. Analysis of the relationship of DP versus RDP/DP for vegetated and unvegetated examples of 43 sand dunes sites from all over the world can highlight the effect of high wind power on the vegetation cover of sand dunes (2). The line that differentiates the vegetated dunes from the unvegetated ones indicates that when RDP/DP is low (multidirectional winds), wind energy is distributed on more than one slope of the dune and the energy exerted on each slope is lower than the same DP with high RDP/DP. Eq. (4) is the mathematical expression of this line:

$$M = \frac{DP}{1000 - \left(750\frac{RDP}{DP}\right)}. \tag{4}$$

Sand dunes in areas where the annual average rainfall is $\geq$ 50mm are unvegetated and mobile under wind conditions where $M > 1$ (according to equation (4) and are covered by vegetation when $M < 1$. Dunes where $M < 1$ and

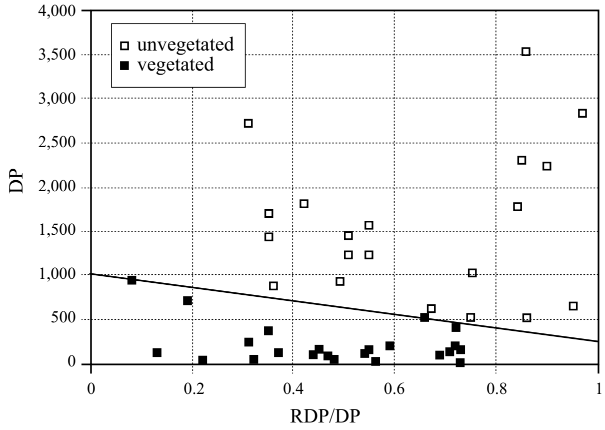

Fig. 2. DP versus RDP/DP for 43 vegetated and unvegetated sand dunes in areas where the annual average rainfall is ≥ 50 mm.

which are bare of vegetation are probably under human pressure (overgrazing or trampling) and will be covered by vegetation naturally once human pressure is stopped. Such a process took place along the Israeli coasts when the grazing, trampling, etc., stopped in 1949 [28]. Vegetated dunes that are under $M > 1$ are either dunes that were stabilized artificially as part of sand dune management, or dunes that were covered by vegetation in the past when the climate was different and M was smaller than 1.

4 Conceptual model on the effect of wind power on mobility and stability of sand dunes

The overview in Section 3 has delivered a set of ideas that allow us to conceptualize how wind power and changes in wind power are affecting the amount of vegetation cover. This relationship between wind power and vegetation cover can be recapitulated by a hysteresis curve (3). When climate change occurs in the form of a decrease in wind power, vegetation will start covering the sand dunes in increasing amounts as the wind power decreases below 1000 DP. When DP is below 200 this process is consummated as vegetation cover reaches the maximum that dune sand can support. However, when this process is reversed, an increase of wind power over vegetated dunes will not cause the total extinction of vegetation when DP increases above 1000. The microphytes, annuals, shrubs, bushes or trees will form an effective buffer between the wind and the sand [29]. There is a threshold for the destruction of vegetation by tempest winds but the value of the wind power for this occurrence is not so clear. The Beaufort wind scale indicates that large trees can be uprooted by an average wind magnitude of 51 knots (26 m/s).

The lines of the hysteresis are the connections of the points of stability. Sand

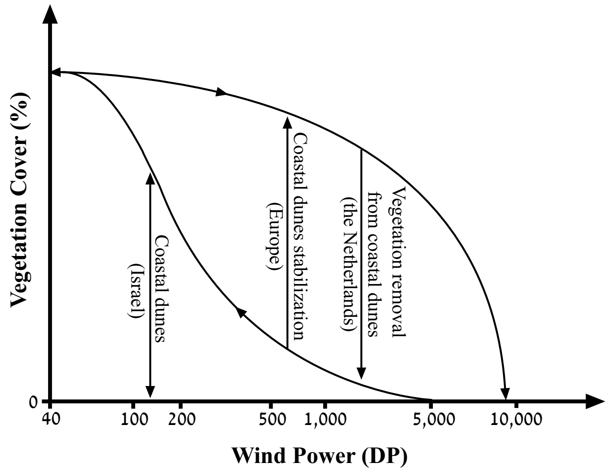

Fig. 3. Hysteresis curve related to changes in wind power and vegetation cover. For explanations see text.

dunes with any amount of vegetation are stable in their state when they are on these lines. Any natural change in the wind power or artificial change in vegetation cover will bring the dune to a new position on the hysteresis line. Fig. 3 shows the changes that have occurred in the Western European coastal sand dunes during the last 200 years when naturally mobile dunes were artificially stabilized and came to a stable position at the upper reverse side of the hysteresis curve with maximal vegetation cover. The artificial removal of vegetation on the parabolic dune in North Holland [30], brought the Dutch coastal dunes to a lower stable point of mobility. The coastal dunes of Israel were active and without vegetation because of strong human impact but their vegetation recovered soon after 1949 when the human pressure was curtailed on account of the low wind power on the Israeli coast (Fig. 1). A similar and quicker response occurred in the more arid Negev Desert's sand dunes because the wind power there is even lower (3).

5 Conclusions

1. The limiting factor for vegetation on dune sand is erosion by high wind power.

2. The amount of rainfall is not a limiting factor. In other words, desert sandy ecosystems are not controlled by water (rainfall) but by wind power.

3. Change in wind power will cause a change in vegetation cover along hysteresis lines of stability. Mobile bare sand dunes will stay unfixed until they are stabilized artificially or if the climate is changed to a wind power of several hundreds DP or less. Stabilized sand dunes can keep their stabilization state even if the wind power increases to values that normally prevent plants from

sprouting on shifting sand ($DP > 1000$).

4. Fixed dunes will stay stable unless some unnatural disturbances mobilize them or the wind power increases to values much higher than the current wind power known in Western Europe or North America. Simulation demonstrates that wind power of $DP > 6,000$ may cause natural destruction of vegetation on coastal dunes. Such high DP exists only in Antarctica.

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