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Review Article

Sand Dunes Reviewing: Wind Effect and Dunes Classification

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ABSTRACT

Drylands are distributed in many parts of the world. The combined effects of land mismanagement, unsustainable use of water, and climate change have caused the transformation of many areas into drylands, and as a result, increase desert areas and the formation of aeolian sand dunes. Due to the increase in construction activities in drylands areas, more descriptions of the formation of soils in aired zones, the effect of wind erosion on these soils, and their classification and movement are required so as to assess their effect on such activities. This paper described the wind action on aeolian dunes, it's reviewed the occurrence, movement, and classification of dunes. The effect of direction and intensity of the wind on the length, height, and location of dunes was presented. The saltation, suspension, and creep movements of sand grains were discussed. The challenges of the classification of the sand dunes were, also, included as a part of this review. It was found that there is a significant effect of the dune morphology on sediment movement and "wind flow lines". The determination of dune morphology is related to many interdependent factors, the assessment of these factors is difficult. Due to their varying sizes and shapes, sand dunes classification was found to be a challenging.

1. Introduction

Drylands are distributed in many parts of the world including Australia, southern Africa, North Africa, North America, Central Asia, and the Middle East as shown in Figure 1. The combined effects of land mismanagement, unsustainable use of water, and climate change have caused the transformation of many areas into drylands. As a result, the desert areas and the formation of dunes increase [1].

Aeolian desertification is defined as land degradation in arid, semiarid, and semi-humid regions with the occurrence of blown sand activities. Such actives include deflation, ground surface coarsening, and sand dune formation on former non-desert areas as the main mark. This is a result of various factors such as upsetting the fragile ecological balance (under the conditions of arid, semiarid, and semi-humid), and the overuse of land [2]. Aeolians are those affected by wind action. This action includes transport, erosion, or deposition arising from the movement of air over the surface of Earth. Mainly, aeolian sediments are divided into three categories: sand sheets, sand dunes, and loess blankets [3-5].

Sand dune can be defined as a ridge or mound formed by wind deposition of loose sand. The size ranges of dunes are from (more than one meter) to several kilometres [4]. They are, either, grouped together to form fields of a sand dune or are in the form of an isolated ridge [4]. Dunes are found in many different places and, according to their geographical occurrence, can be classified as "inland or continental dunes", "coastal or sea-shore dunes", "riverbank dunes", and "lakeshore dunes" [4]. Dunes have

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particular characteristics of changing their length, height, and location depending on the direction and intensity of the wind [6]. Al-Soud and Al-Shakarchi [7] claimed the more influential the wind, the more it affects the soil. Sand-sized particles gathered as dunes of various shapes and sizes after being transported by wind. However, due to the increase in construction activities in dryland areas, more descriptions of the formation of soils in aired zones are required. The effect of wind erosion on these soils, and their classification and movement are necessary so as to assess their impact on such activities.

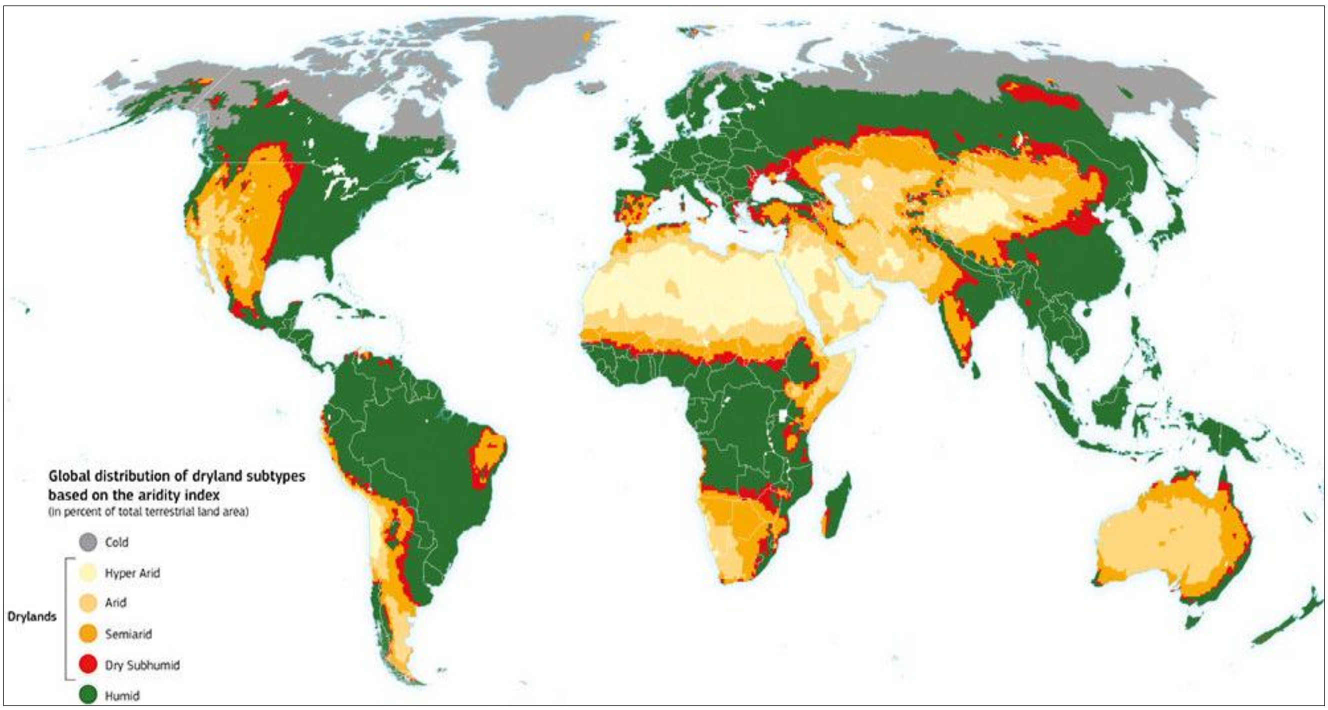


Fig. 1: Global distribution of the drylands (Mcsweeney [8])

2. Wind Erosion and Sand Dune Movement

The degradation of soil by wind and water is referred to as "erosion". Erosion, transportation, and deposition are the three steps of the aeolian process. Wind erosion is similar to water erosion in terms of its impact on the soil [7, 9]. Under the arid condition, wind scouring is much more severe than rainwater or stream water erosion [9]. Wind erosion is more common in places where the temperatures are consistently high and where there is a dearth of precipitation. Wind movement and circulation are extremely important factors in wind erosion [7]. The particles eventually settle down to earth when the aerodynamic force applied to them are less than the gravitational force [10]. The following factors represent the main causes of wind erosion [11]:

1. ferocious wind (that sweeps over a vast region).
2. vegetation (that is stunted or scant).
3. deteriorated, mobile, barren, and dry soil.

Fryberger and Dean [12] divided the patterns of annual winds into "complex", "bimodal" and "unimodal". There are more than two different modes for the wind in the "complex" pattern. While the direction of the seasonal wind in the "bimodal" regime is divided into two directions or modes. In the "unimodal" regime, almost, there is one direct for winds blowing throughout the year. The wind impacts the soil by desiccating the top layer, drying it off, and removing soil particles by deflation. The susceptibility of soil particles to erodibility by wind is mainly related to particle diameter as shown in Table 1. It can note that soil particles with higher grain size are less susceptible to wind erodibility. Data in Table 1 may be used to classify soils according to their sensitivities to wind [13].

Bagnold [14] defined the essential principles of wind erosion and classified it into three types based on particle size, these are saltation, suspension, and creep (see Figure 2). He claimed that sand dunes are primarily conveyed by the wind in saltation. The saltation is formed by the bouncing and jumping motion of sand particles caused by the action of direct wind. Soil particles gather a lot of forwarding momentum from the pressure of wind on them, and their horizontal velocity accelerates from the time the grains start to ascend until they hit the ground. They either bounce and continue their movement in saltation or they lose most of their energy by striking other grains, causing them to climb upward and sink below the surface or becoming part of the surface creep movement. Fine grains of size 0.1 mm to 0.5 mm (in diameter) make up the majority of soil moved by saltation. This size range, almost, is formed in most forms of sand dunes [15]. The majority of the particles' movement in saltation is carried below a height of 60 cm to 90 cm, [14, 16-17].

Table 1. Classification of different particle diameters and wind susceptibility

Fraction	Particle diameter, (mm)	Wind susceptibility
A	< 0.42	Highly erodible
B	0.42 to 0.84	Difficulty erodible
C	0.84 to 6.4	Usually no erodible
D	> 6.4	Non-Erodible

The direct impact of saltating on too heavy soil particles (with a diameter of 0.5 mm to 1.0mm) to be dislodged and rebounded into the air produces surface creep, which is the sluggish movement of the soil surface. Surface creep is roughly proportional to the number of erosive grains larger than 0.5 mm in diameter in cultivated soils and over 0.25 mm in dune sand [14, 17-18]. Tiny soil particles, with diameter <0.1 mm, are transported by the suspension (see Figure 2). These particles have a lesser falling velocity than "turbulent winds' rising velocity", and after being dislodged from the surface (by saltating grains, or mechanical disturbance) they are directed by the "wind's characteristic behavior". As a result, these particles transport to a vast height and across long distance. Suspension transport happen when air turbulence produces "vertical velocity variations" higher than the "grain settling velocity" [4, 14]. In spite of the fact that some or all the movement modes of soil particles may be active at the same time, none of these modes would be possible without the first type of movement (i.e. saltation). In other words, to eliminate these modes of movement, saltation should be eliminated first, then the wind erosion will be eliminated too.

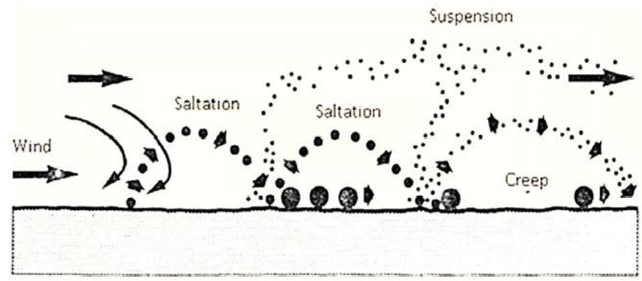


Fig. 2: Methods of grains movement (FAO [19])

The transportation of the sediment individual grains by wind is governed by three forces, these are gravity force (FG), drag force (FD), and lift force (FL) as shown in Figure 3. The grains are kept at the ground surface due to the effect of FG, and the movement of sediment grains along the surface of the ground is controlled by FD, while the wind moving over the ground surface creates different pressures that lead to producing FL. When the wind across the lower part and the middle part of the sand grain with relatively low velocity and across the top part of the grain with high velocity the FL is produced. To start the grain movement, first, the stationary grain vibrates, then when the FL exceeds the FG the vibrated grain begins its movement [20-22].

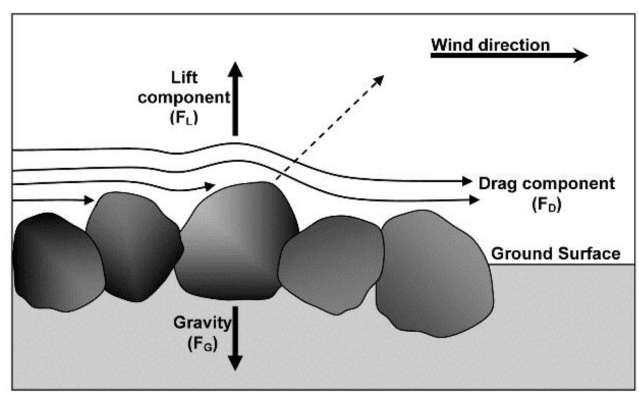


Fig. 3: Forces operating transported of grain of sediment (from Sloss et al. [21].

There is a significant effect of the dune morphology on sediment movement and "wind flow lines". The field observation of Bristow et al. [23] (Figure 4) showed that when the wind is virtually perpendicular to the crest-line, flow separation occurs. Along both windward and leeward slopes, flow line is diverted locally. The superimposed dunes formation is encouraged by the wind movement along the sides of the dune. For dunes with convex flanks, such formation is frequently best developed, particularly on the eastern slope, which faces south-westerly winds. The windward dune flank is concave, the wind is locally focused, and where the dune flank is convex, the wind is deflected. When the wind is virtually perpendicular to the crest-line, flow separation occurs. Along both lee and windward slopes, flow lines are diverted locally, see Figure 4.

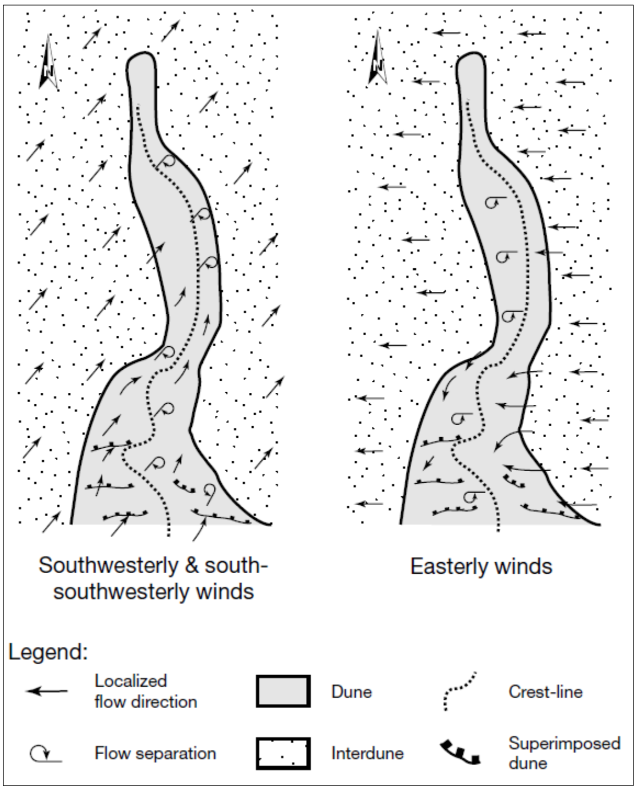


Fig. 4: Effect of the dune morphology on sediment movement and "wind flow lines"

3. Sand Dunes Classification

Due to their varying sizes and shapes, sand dunes classification is challenging. There are three variables controlling the sand pilling into dunes with a specific form. Two of these variables are climatic while the third is sedimentary. The climatic variables are wind direction, frequency, speed, and the use of vegetation as a cover. While the sedimentary variable is related to the grain size of the soil particles [6, 24]. There are three categories of simple dunes. In the first category, the topographic impediments are controlled the growth of dunes. The second category represents the self-accumulating dunes. While that last one, the vegetation is heavily impacted the growth of dunes [4].

Other classification of sand dune is based on geographical location, metal structure, and activity of sand dunes. According to their geographic location dunes can be classified into coastal dunes (grow at the back of a beach), and desert sand dunes. The coastal dunes generate by the movement of the air (aeolian transport) rather than wave, current, or tide action. The initiation of aeolian transportation of coastal dunes are influenced by many factors like wind velocity, beach shape, sediment properties, the degree of roughness, and the moisture content [22, 25]. The transport factor of desert sand dunes is the wind, this factor is the most important factors affecting the formation of the surface of desert areas. While the primary sources of these dunes are the surrounding mountains. The low vegetation and drought are factors that help to formation of desert dunes [25]. According to metal structure, desert sand dune can be classified into limestone dunes, gypsum dunes, and quartzing dunes. While the activity of dune divides desert dunes into the most common active dunes, and the limited distribution semi-active dunes. The climate imposes an external force that affects the activity of aeolian dunes. Dry and /or windy environments are controlling the active or bare dunes, in the contrast, the quiet and/or the humid settings are affecting the activity of vegetated (inactive) dunes [26].

However, there are three categories of active dunes, these categories are mainly depending on the movement of the dune as shown in Table 2.

The main categories of active dunes shown in Table 2 can be subdivided into different shapes of dunes according to the alignment of the dunes' crest with respect to net sand transportation as shown in Table 2. In addition to subdivisions shown in Table 2 there are other shapes of dune such as parabolic and Longitudinal dunes. According to Shehata and Al-Rehaili [9], parabolic dunes are U-shaped, pointing downwind (opposite the barchan dunes), and move by eroding downwind terrain and depositing it in a dune form downstream, Figure 5. While longitudinal dunes are aligned parallel to the direction of the prevailing wind and move in a sinusoidal pattern.

The accumulation of sand in dunes affect by different factors. The topographical barriers (cliffs) cause sand accumulation due to "airflow obstruction" which in turn produces sand dunes devoid of vegetation. Also, the changing in aerodynamics or bed roughness in open terrain areas produces sand dunes devoid of vegetation. While vegetated dunes form due to vegetation-induced accumulation [6].

Table 2. Main categories of active dunes (modified after Tsoar, [6])

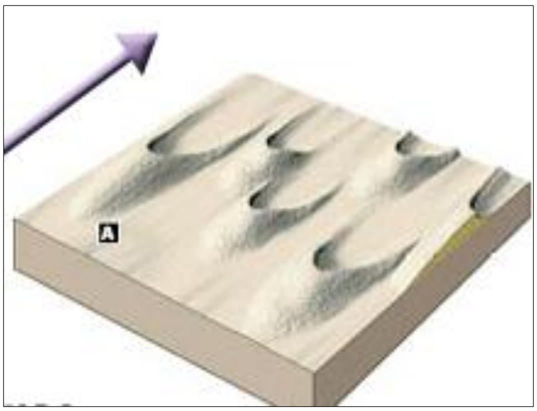
Category No.	Type of Active dune	Description	Representative dunes
1	Migrating dunes	The entire dune body moves forward with little or no change in shape or size	Barchan and transverse dunes
2	Elongating dunes	As time passes, the dunes lengthen and get longer	Linear dunes
3	Accumulating dunes	There is little or no net advance or elongation in the accumulating dunes	Star dunes

Table 3. Subdivided categories of active dunes (modified after Bishop et al. [28])

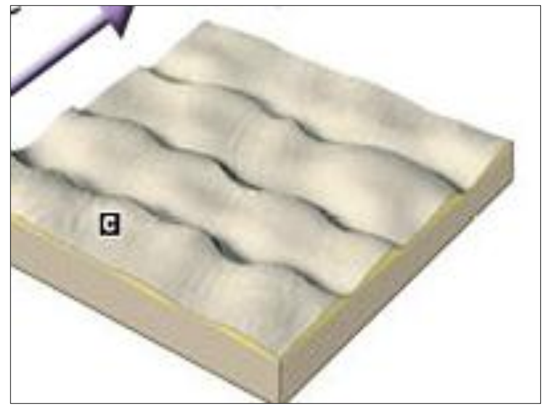
Category No.	Main of active dunes	Subdivided categories	Description
1	Transverse dune	Dome dune	A single, generally transverse dune that has a no-slip face
		Barchan dune	Dune with a crescentic plane shape and a free transverse dune with the crescent opening downwind.
		Transverse dune:	The crest of dune ridge that is transverse to the primary wind's direction of travel and which move mostly in that direction
		Reversing dunes	As the wind shifts through 180 degrees, the direction of the dune reverses
2	Linear dunes	Seif dune	A linear dune with a curved, sharp-crested shape
		Sand ridge	Linear dune that is somewhat vegetated and generally larger than a seif
3	Star dunes	Star dune	A big dome-shaped or pyramidal dune with arms
		Network dune	When several transverse dunes come together, each one is aligned to a different wind in an annual pattern that is very different from one year to the next

Among the shapes of dune shown in Table 3 and Figure 5, the barchan dune represents the fastest moving type. When the wind is strong or when this wind is more frequent this affects the vegetation found on barchan dune [27]. The sand accumulated in the shape of barchan is dry and has a low relative density, such that, each year and depending on their size, barchan dunes can move from a few meters to about ten meters. A huge dune's movement includes the transfer of a considerable amount of sand; hence it moves at a slower rate than a smaller dune [9]. Nevertheless, it should be mentioned that the vegetation cover on dunes has an important role in the movement of these dunes. Therefore, the transport capacity of sand and variability of wind direction should be studied with the corporation of vegetation cover on dunes [12, 29]. While the classification of the vegetated dune is affected by the unidirectional winds (strongest wind), therefore, the longitudinal, oblique, or transverse dunes classification should be related to "effective transporting wind". The Effect of wind regimes on different dune types is presented in Table 4. According to Wasson & Hyde [30] and Thomas [31], in general, there is no control exercised by grain size on the size and morphology of dunes.

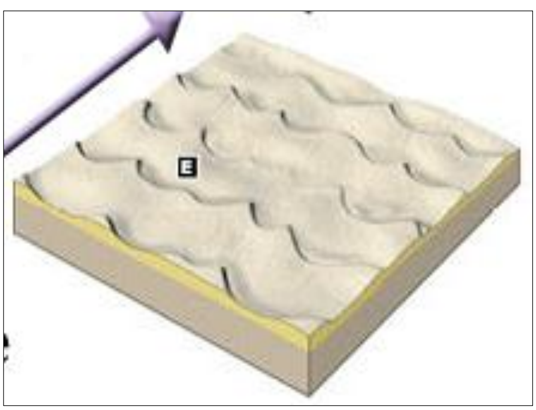
Transverse dunes resemble gigantic ripples being wavy and irregularly interconnecting, and transverse to the main direction of sand laden wind. When the supply of sand is not sufficient, the transverse dunes are often partitioned by the wind into barchans, the classic crescent shaped dunes with tails extending downwind. The occurrence of two dominant wind directions causes on tail of a barchan to grow longer giving a seif. In seifs the long tails sometimes link dunes into a continuous chain constituting a longitudinal dune running more or less parallel with the major wind. Parabolic dunes have a shape similar to barchans, except that they form with their apexes in the opposite direction. The probably develop from transverse dunes after some vegetation removal, and they are common along sandy ocean and lake shores[32-34].



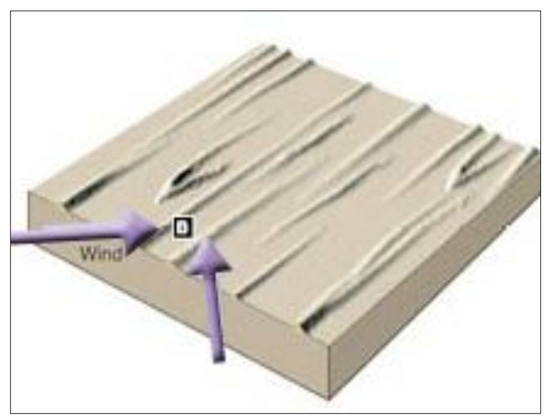
Barchan Dune



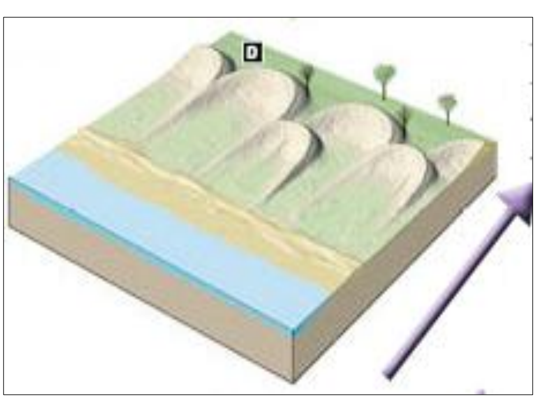
Transverse Dune



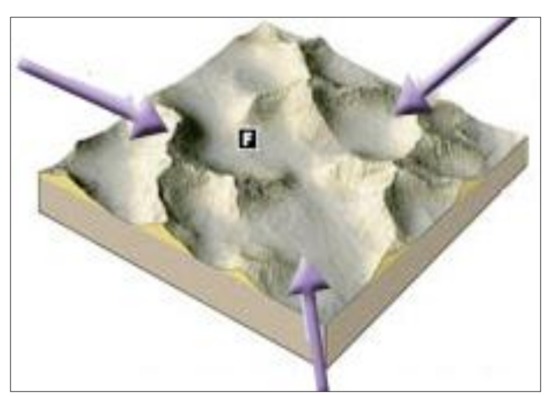
Barchan Dune becoming Transverse Dune



Linear Dune



Parabolic Dune



Star Dune

Fig. 5: Shapes of sand dunes (the arrow indicates the wind direction)

Table 4: Effect of wind regimes on dune type (after Pye and Tsoar [4])

Wind regimes	Dune type
Almost unidirectional wind regimes	Large barchans, transverse dunes, and dome dunes
Markedly acute bidirectional wind regimes	Linear dunes of the seif type
Obtuse bimodal and multimodal wind regimes,	Reversing transverse dunes and star dunes
Unidirectional effective wind regime	Elongate parabolic dunes
Bimodal and complex wind regimes	Parabolic dunes

4. Conclusions:

The increasing of different construction activities in drylands areas requires more description of the formation of soils in aired zones. The assessment of wind erosion reaction on dryland soils, the classification of dunes, and the studying of their movement may helpful in decreasing the unfavourited effect of such soils on these activities. This paper described the wind action on aeolian dunes, it reviewed the occurrence, movement, and classification of dunes. Factors that affect the length, height, and location of dunes were presented, and the movement of dune sand grains (by saltation, suspension, and creep) was discussed. It also included a review of issues related to the challenges of the classification of the sand dunes. The main conclusions drew from this review are as follows:

1. It is difficult to assess the interdependent factors that control dune morphology. The direction of the wind with respect to the crest line of the dune is one of these factors. The movement of sediment and "wind flow lines" are highly affected by the dune morphology.
2. There is a direct relation between climatic and sedimentary factors on the one hand and sand dune formation on the other. The most prominent climatic factors affecting the formation of sand dunes are the presence of vegetation cover and the characteristics of the prevailing winds in terms of speed, frequency, and direction. While the size of the soil particles represents the sedimentary factor.
3. Classification of sand dunes presents a major challenge. This is due to the different shapes of sand dunes on the one hand, and their different sizes on the other.
4. The growth of simple dunes is controlled by topographic impediments, self-accumulating, and vegetation. Also, the geographical location, metal structure, and activity of sand dunes showed highly effect on the classification of dunes.

Conflict of Interest

The authors declare that they have no conflict of interest

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