Why Do Active and Stabilized Dunes Coexist under the Same Climatic Conditions?

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Sand dunes can be active (mobile) or stable, mainly as a function of vegetation cover and wind power. However, there exists as yet unexplained evidence for the coexistence of bare mobile dunes and vegetated stabilized dunes under the same climatic conditions. We propose a model for dune vegetation cover driven by wind power that exhibits bistabilty and hysteresis with respect to the wind power. For intermediate wind power, mobile and stabilized dunes can coexist, whereas for low (or high) wind power they can be fixed (or mobile). Climatic change or human intervention can turn active dunes into stable ones and vice versa; our model predicts that prolonged droughts with stronger winds can result in dune reactivation.

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Sand dunes form an important, unique, and complex ecological [1] and physical [2] system. Approximately 20% [3] of desert areas are covered by sand dunes, some of which endanger human settlements, agricultural fields, roads, etc. (e.g., [4]). Sand dunes may be either active (mobile) or fixed, as determined primarily by vegetation cover and wind power. Climate changes and human activities may therefore transform fixed dunes into mobile dunes, and vice versa [5], and may even accelerate desertification processes. It is thus important to understand dune dynamics and their response to various climatic changes and human activities.

One of the most interesting phenomena related to sand dunes is bistability; i.e., under the same climatic conditions (mainly wind power and precipitation) and in the same geographical area, it is possible to find both active and fixed dunes [Fig. 1(a)]. The underlying mechanism for this bistability is not yet clear. Recently, Tsoar [6] suggested that it is driven by the interaction between wind and vegetation. This Letter will develop a simple, physically motivated model to explain the bistability and hysteresis of sand dunes.

Dunes are driven by the wind [6,7], but vegetation covering them weakens this impact. On one hand, even the action of very strong winds may be masked by vegetation leaving the dunes immobile. On the other hand, even relatively weak winds may lead to sand mobility when dunes are bare. Moreover, wind also affects the vegetation cover; when wind becomes stronger the vegetation cover decreases, a fact that further enhances dune mobility, which in turn further reduces vegetation cover. This feedback mechanism underlines the model we propose below.

Wind power is usually expressed by aeolian geomorphologists as a drift potential (DP) [6,8]. Theoretical and empirical studies have shown [2,8,9], that DP is proportional to the potential sand volume that can be transported by the wind trough a 1 m wide cross section per unit time (in most cases, given as per year). DP is given by

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

where U is the wind speed (in knots: 1 knot $= 0.514$ m/s) measured at a height of 10 m and the average is over time; U_t is a minimal threshold velocity ($=12$ knots) necessary for sand transport [8]. Still, the DP is a *potential* sand drift, with the actual sand drift further depending on the mean grain diameter, the degree of surface roughness, the amount and type of vegetation or crust cover, the amount of moisture in the sand, and the uniformity of the wind direction. According to Fryberger [8] wind energy can be classified as follows: $\mathrm{DP} < 200$, low energy; $200 \leq \mathrm{DP} < 400$, intermediate energy; and $\mathrm{DP} \geq 400$, high energy.

A striking example of the dune bistability phenomenon, i.e., mobile barchan dunes and stabilized parabolic dunes [Fig. 1(a)], is found in northeastern Brazil [10]. Here the average annual rainfall is 2.4 m and the DP is over 1000. In spite of the extremely high rainfall, many dunes are active due to the strong winds.

A vegetated dune can naturally become active when the wind power is sufficiently high to cause the decay of vegetation. Once active, only a climatic reversal to much weaker winds which do not suppress vegetation growth, will allow reestablishment of vegetation and stabilization of the dune. These dynamics describe hysteresis behavior. Natural changes in windiness or forced changes in vegetation cover (e.g., overgrazing, clear cutting, or forced stabilization by planting) may shift the dune into a new state. An example of such a transition is the clear cutting of vegetation on dunes in North Holland that took place in December 1998 (DP = 1570) [11], which led to the dunes remaining bare and mobile until today.

In places with very weak wind power (low DP), the dunes have only one stable fixed vegetated state; here we assume that the precipitation is above the threshold needed for vegetation growth (∼80 mm/yr, based on observations in the Negev Desert). In these cases, the dunes can be active due to either anthropogenic pressure or prolonged

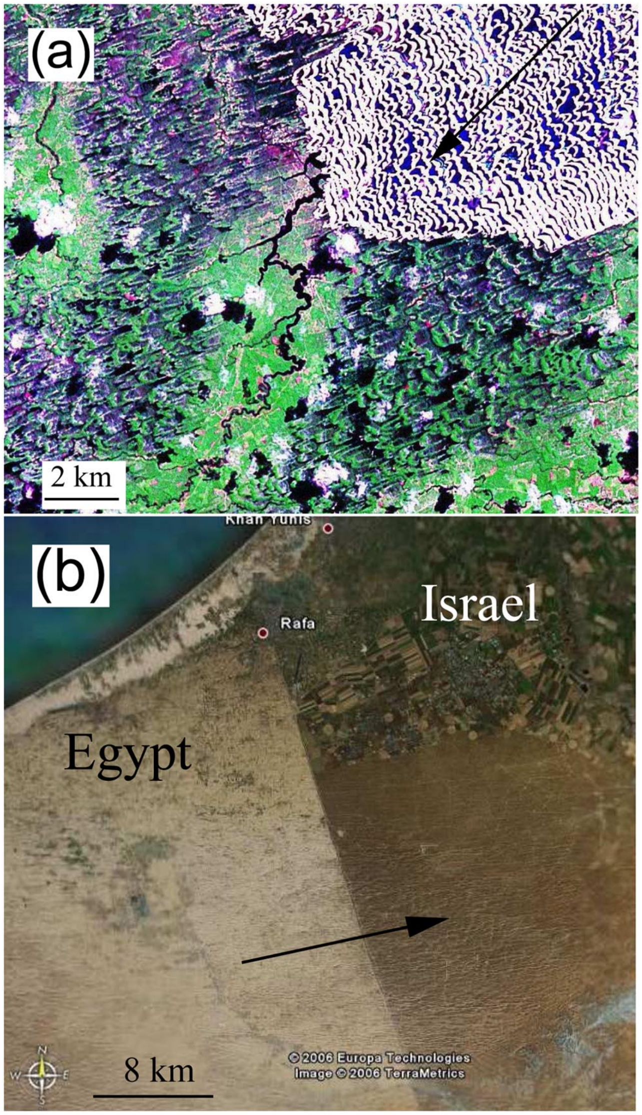

FIG. 1 (color online). (a) Lençóis Maranhenses dunes in northeastern Brazil (43° W, 2° S); a field of active barchan dunes (upper right corner) coexist with fixed vegetated parabolic dunes. Landsat Satellite image. [Landsat imagery courtesy of NASA Goddard Space Flight Center and USGS Center for Earth Resources Observations and Science.] (b) Satellite image (Google Earth) of the Israel-Egypt border area showing high contrast in albedo between the bright active Egyptian dunes and the darker fixed vegetated Israeli dunes. Arrows indicate the prevailing wind direction.

drought. This occurs, for example, at the Israeli-Egyptian border [Fig. 1(b)], where there is a clear visual difference between the active dunes on the Egyptian side and the vegetated and almost fully stabilized dunes on the Israeli side [12]. This difference is attributed to wood gathering, overgrazing, and trampling of the sand crust on the Egyptian side, practices that have been prohibited on the Israeli side since the establishment of the border in 1982. Once this anthropogenic pressure ceased on the Israeli side, the dunes took on their natural state of vegetated, fixed dunes within two years, as dictated by the area's weak wind power and above-threshold precipitation.

We formulate here a general model of wind-vegetation-dune interactions without going into the details of dune types. We assume that wind power is the dominant factor affecting dune mobility in areas where the annual precipitation is above the threshold needed for vegetation development (50–80 mm per year [6]). The impact of vegetation cover on sand transport involves complicated processes (cf. [13,14]). Vegetation acts to reduce wind-based sand transport as it extracts momentum from the air, reduces wind velocity, masks the sand surface from direct wind action, and traps sand particles. The sand transport depends on the height, roughness, and concentration of plants (e.g., [15]). In the absence of a complete, accepted theory for the coupling between sand transport and vegetation, we adopt a simple modeling approach that is consistent with basic physical principles [16].

The model we propose is

$$\frac{dv}{dt} = \alpha(v+\eta)\left(1-\frac{v}{v_{\max}}\right) - \varepsilon\,\mathrm{DP}\,\theta(v_c - v)v - \gamma\,\mathrm{DP}^{2/3}\,v. \tag{2}$$

The dynamical variable is v, the vegetation areal cover density, which values between 0 (bare dune) and $v_{\max}$, where for completely vegetated dune $v_{\max} = 1$. The vegetation growth rate, $\alpha(v+\eta)(1 - v/v_{\max})$, is logistic growth [production $\alpha(v+\eta)$ multiplied by resource competition $(1 - v/v_{\max})$] [17] where "η" is a "spontaneous" vegetation factor growth that describes an average growth rate for even bare dune due to soil seed banks, underground roots [18], and seed carried by wind, animals, etc. Logistic models are often used to describe hysteresis phenomena of ecological and economical systems [19].

The second term on the right-hand side of Eq. (2), $\varepsilon\,\mathrm{DP}\,\theta(v_c - v)v$, represents the effect of sand movement on vegetation (such as root exposure and plant burial by sand) and since it is a mortality term it is proportional to v. v_c is a critical vegetation cover above which sand transport sharply decreases [20,21]. The Heaviside step function $\theta(v_c - v)$, which is 1 when $v < v_c$, while otherwise is zero, reflects the fact that for high vegetation density, $v > v_c$, the surface is effectively protected from wind action [15]. The speed of dune migration is proportional to the sand flux, which is self proportional to DP. Thus a change in dune height is also proportional to DP [2,8] and hence the erosion or accumulation of vegetation due to sand transport is proportional to DP. ε is a proportionality constant that may have different values for different plants.

The last term in Eq. (2), $\gamma\,\mathrm{DP}^{2/3}\,v$, stands for a reduction in vegetation cover due to direct wind action that can increase evapotranspiration and uproot, erode, or suppress the growth of vegetation [22]. Generally, wind drag is proportional to the square of the wind speed [2] while DP is proportional to the cube of the wind speed [Eq. (1)]. Thus, $\mathrm{DP}^{2/3}$ may represent wind drag on vegetation and hence the vegetation growth suppression due to direct wind action. This term is proportional to v, as it is basically a mortality term. γ is a proportionality constant. The term, $\gamma\,\mathrm{DP}^{2/3}\,v$, unlike the other terms in Eq. (2), acts even when the dune is maximally vegetated.

Although it is possible to reduce the model (2) to contain only four independent parameters we choose to follow the seven original parameters to allow easier physical interpretation. The parameter values that we use are: $\alpha = 0.1\ \mathrm{yr}^{-1}$ which is a typical growth rate for dune vegetation (see [17]); $\eta = 0.2$ is estimated as $\frac{dv}{dt}/\alpha$ starting from bare dune and when $\mathrm{DP} = 0$, $v_{\max} = 1$ represents ideal vegetation growth conditions: $v_c = 0.2$ [7,23], $\varepsilon = 0.001$, and $\gamma = 0.0008$. Both ε and γ can be estimated from field experiments.

The proposed model [Eq. (2)] has two stable stationary states, A and F, representing active and fixed dunes, respectively. The vegetation cover density under which active and fixed states may interchanging $v_{a,f}$ is

$$v_{a,f} = -\Gamma_{a,f} + \sqrt{\Gamma_{a,f}^2 + \eta v_{\max}}, \tag{3}$$

where

$$\Gamma_{a,f} = v_{\max}[-1 + \eta/v_{\max} + \varepsilon\,\mathrm{DP}\,\theta(v_c - v)/\alpha + \gamma\,\mathrm{DP}^{2/3}/\alpha]/2. \tag{4}$$

The active dune state v_a is valid when $v < v_c$ and the fixed dune state v_f, is valid otherwise. For $\mathrm{DP} = 0$, $v = v_{\max}$.

Figure 2(a) shows the stable stationary states as a function of DP. For a wide regime of DP values, both the fixed and active dune states coexist, indicating the hysteresis and bistability of the model. This dune hysteresis may be described as follows: starting from very low DP, only the fixed dune solution v_f exists; when the DP slowly increases, this solution persists until the very high $\mathrm{DP} = \mathrm{DP}_2$ is reaching at which point $v_f = v_c$. The DP at this point is given by

$$\mathrm{DP}_2^{2/3} = \alpha(1 - v_c/v_{\max})(\eta + v_c)/(\gamma v_c). \tag{5}$$

Beyond this point, the system switches to the active dune state, A. When DP is then slowly decreased, the solution continues to be the active dune state until a very low DP (DP_1), at which point it switches to the fixed dune state. DP_1 can be approximated as

$$\mathrm{DP}_1^{1/3} \approx (\mathrm{DP}_2^{2/3}\gamma/\varepsilon)^{1/3} - \gamma/(3\varepsilon). \tag{6}$$

Thus, as DP_2 decreases, DP_1 also decreases.

The critical vegetation cover v_c varies for different geographical locations, from $v_c \approx 0.14$ for the Kalahari desert [23] to $v_c \approx 0.35$ for Australian deserts [7]; v_c is sometimes difficult to measure and may have only marginal accuracy. The various v_c values found in nature may indicate different dynamic scenarios predicted by our model. More specifically, DP_2 [Eq. (5)] decreases drastically with increasing v_c, which means that dunes with higher values of v_c (like the Australian dunes) can be reactivated at lower DP values (weaker winds), whereas for dunes with lower values of v_c (like the Kalahari dunes) stronger winds are needed for reactivate them. Following Eq. (6), DP_1 also decreases with increasing v_c but more slowly as compare to DP_2. Thus, as v_c increases, the hysteresis diagram shrinks and shifts to the left, mainly since the fixed dune branch F becomes smaller; see Fig. 3(a).

Human intervention may cause active dunes to become stable or stable dunes to turn active. The model shows that vegetated dunes with higher DP values are more vulnerable to activation as only a relatively small disturbance in vegetation cover such as, clear cutting or overgrazing may shift the system to the lower branch of activated dunes. The reactivation of some Netherlands coastal dunes described above can be regarded as an example of this transition, which is seen in Fig. 2(b). The graph shows numerical solutions of Eq. (2) with different initial pertur-

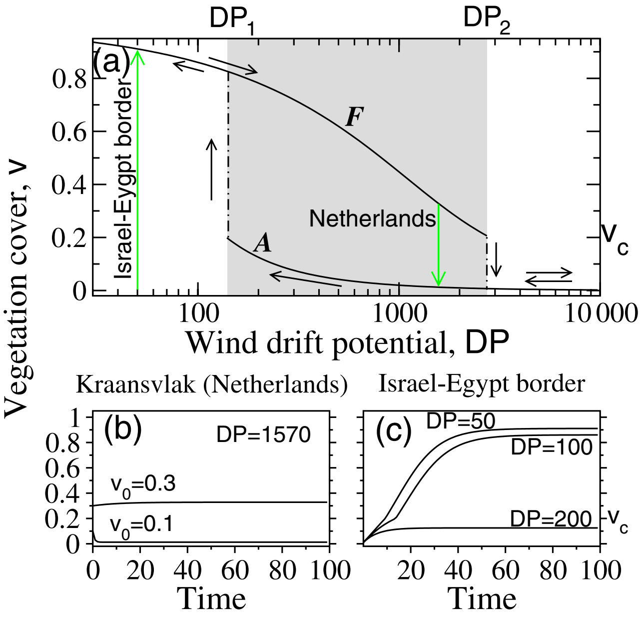

FIG. 2 (color online). (a) Stable states diagram showing vegetation cover v vs DP. The gray area indicates the domain of bistability. The arrows indicate the hysteresis scenario, and the dash-dot vertical lines indicate the transition from fixed to active dune states and vice versa. Solid lines indicate stable states. Parameter values used are: $v_{\max} = 1$, $v_c = 0.2$, $\epsilon = 0.001$, $\alpha = 0.1$, $\gamma = 0.0008$, $\eta = 0.2$. For these parameters, $\mathrm{DP}_1 = 139$ and $\mathrm{DP}_2 = 2828$. The vertical arrows indicate two examples shown in panels b and c. (b) An example of transition from a fixed dune to an active dune state (Netherlands case). Time evolution (in arbitrary time units) of vegetation cover v for $\mathrm{DP} = 1570$ for different initial conditions ($v = 0.3$ and $v = 0.1$). The upper curve converges to the fixed dune F state, while the lower curve (that is associated with large disturbance) converges to the active dune A state. (c) Same as b, but for different DP values, (Israel-Egypt border case), starting from $v = 0.01$. For $\mathrm{DP} = 50$ and $\mathrm{DP} = 100$, the asymptotic state is the fixed dune state F, whereas for $\mathrm{DP} = 200$, it is the active dune state A.

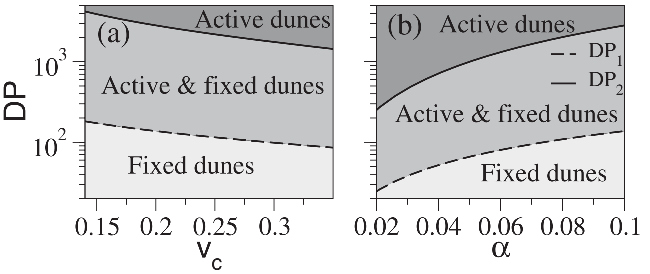

FIG. 3. (a) Active to fixed dune transition point DP_1 [Eq. (6)] and fixed to active dunes transition point DP_2 [Eq. (5)] as a function of critical vegetation cover v_c. The various gray shadings represent different stability regimes. As v_c increases the fix-active and active-fix dune transitions occur for weaker winds (low DP) (b) Same as (a), but for different growth rates α. As α decreases fix-active and active-fix dune transitions occur for weaker winds (low DP), suggesting that drought conditions are more favorable for transitions from fixed to mobile dune states (desertification process). Parameter values are as in Fig. 2.

bations for $DP = 1570$ (which is close to that of the Dutch dune area). The asymptotic behavior of the system depends on the initial state; if the initial vegetation cover is above v_c, v converges to the fixed dune branch F; otherwise it converges to the active dune branch A.

In places with very low wind power the dune has only one stable state, which is vegetated and fixed, suggesting that human intervention is likely to be the dominant factor causing the dunes to turn bare and become active. An example of such a phenomenon is the dunes at the Israeli-Egyptian border mentioned above ($DP \approx 50$); see Fig. 1(b). Figure 2(c) shows the stabilization evolution for three different values of DP starting from a very low vegetation cover ($v = 0.01$), such as that on the bare, active dunes on the Israeli-Egyptian border. For $DP < DP_1$, v converges quickly to the fixed, vegetated dune state, with the response curves seeming to reflect to actual data [12,17]. However, our model predicts that with stronger winds ($DP = 200$), the bare and active dunes should remain active even when the anthropogenic pressure is released. In fact, rapid natural recovery of dune vegetation was also reported for parts of North Africa [3].

There is a wealth of evidence for global climate change over the past decades [24]. Global circulation models predict that the global warming trend will persist if the ''business as usual'' scenario [24] continues. Some studies have forewarned that the climate system will become even more extreme, with stronger atypical extreme climate events appearing more frequently (e.g., [24]). It is possible that some desert areas will experience more severe and prolonged droughts with stronger and more frequent wind storms; this could lead to the activation of hitherto fixed dunes, as has been observed in the past decades (e.g., [25]), with severe damage to the environment and the quality of life of millions of people. Our simple model supports such a scenario. Figure 3(b) illustrates the impact of drought on dune activation. We simulate drought conditions by decreasing the vegetation logistic growth rate α in Eq. (2). As α becomes smaller, the hysteresis diagram shrinks, which means that transition from the fixed to the active dune state (DP_2) occurs at weaker winds (smaller DP).

The model we suggest is very simple and does not definitively simulate the complicated process of dune dynamics and the effects of wind direction variability. Thus, our conclusions should be regarded as speculative. Nevertheless, the proposed model may shed light on the dynamical scenarios underlining dune fixation and reactivation processes.

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