Investigating parabolic and nebkha dune formation using a cellular automaton modelling approach

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Abstract

Vegetation plays an important role in shaping the morphology of aeolian dune landscapes in coastal and semi-arid environments, where ecogeomorphic interactions are complex and not well quantified. We present a Discrete ECogeomorphic Aeolian Landscape model (DECAL) capable of simulating realistic looking vegetated dune forms, permitting exploration of relationships between ecological and morphological processes at different temporal and spatial scales. The cellular automaton algorithm applies three simple rules that lead to self-organization of complex dune environments, including nebkhas with distinctive deposition tails that form in association with mesquite-type shrubs, and hairpin (long-walled) parabolic dunes with trailing ridges that evolve from blowouts in association with vegetation succession. Changing the conditions of simulations produces differing landscapes that conform qualitatively to observations of real-world dunes. The model mimics the response of the morphology to changes in sediment supply, vegetation distribution, density and growth characteristics, as well as initial disturbances. The introduction of vegetation into the model links spatial and temporal scales, previously dimensionless in bare-sand cellular automata. Grid resolutions coarser than the representative size of the modelled vegetation elements yield similar morphologies, but when cell size is reduced to much smaller dimensions, the resultant landscape evolution is dramatically different. The model furthermore demonstrates that the relative response characteristics of the multiple vegetation types and their mutual feedback with geomorphological processes impart a significant influence on landscape equilibria, suggesting that vegetation induces a characteristic length scale in aeolian environments. This simple vegetated dune model illustrates the power and versatility of a cellular automaton approach for exploring the effects of interactions between ecology and geomorphology in complex earth surface systems. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: vegetation; parabolic dunes; nebkhas; cellular automata; self-organization

Introduction

Vegetation plays an important role in shaping the morphology of aeolian dune landscapes in coastal and semi-arid environments. Although desert (bare-sand) dune formation has been modelled as a function of wind regime and sediment supply (Wasson and Hyde, 1983; Werner, 1995; Bishop et al., 2002), the influence of the dynamic behaviour of ecogeomorphicological interactions and feedback on vegetated aeolian landforms is generally less well understood (Thomas and Tsoar, 1990; Hesp, 2002). Modelling may aid in understanding complex ecogeomorphicological relationships that influence dune evolution and improve predictions and management of potential environmental changes or anthropogenic impacts on coastal and semi-arid systems. Such applications include: predicting the likely success of remobilizing dormant dune systems (e.g. Arens et al., 2004), managing and mitigating desertification and degradation of semi-arid land (Barbier et al., 2006), assessing the impact of climate change (e.g. Anthonsen et al., 1996; Hugenholtz and Wolfe, 2005a; Marín et al., 2005; Thomas et al., 2005), investigating the effects of changes in land use (e.g. Tsoar and Blumberg, 2002; Levin and Ben-Dor, 2004) and reconstructing conditions responsible for the formation and stabilization of relict systems (e.g. Forman et al., 2001; Forman and Pierson, 2003; Hesse et al., 2003). This paper presents a Discrete ECogeomorphic Aeolian Landscape model (DECAL) capable of simulating realistic looking

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vegetated dune fields and elucidating relationships between ecological and geomorphological processes at different temporal and spatial scales.

Nebkha and parabolic dunes are typical morphologies that involve complex interactions between vegetation and sediment transport to develop their classic shapes. In vegetated dune environments, blowouts may occur due to wind erosion (Hesp, 2002), leading to the development of hairpin or long-walled parabolic dunes with trailing arms (Pye and Tsoar, 1990). Dunes that develop are strongly influenced by climatic conditions and are sensitive to initial blowout size, vegetation type and density, as well as the transport capacity of the wind and sediment supply (Hugenholtz and Wolfe, 2006). Vegetation type and density are linked to the sediment dynamics of the system, as vegetation can reduce transport (Lancaster and Baas, 1998) and limit sediment supply, while vegetation vitality and growth is influenced by sediment burial and erosion (Van der Stoel et al., 2002). Different vegetation species exhibit different burial tolerances, which may determine their preferred location on a dune (Maun and Perumal, 1999). Rather than the larger scale plant communities of parabolic dunes, nebka dunes tend to form in response to individual plants or clumps of plants (Hesp, 2002). They are common at the toe of incipient foredunes or in semi-arid environments (Melton, 1940).

Nebkha and parabolic dune fields may be treated as dissipative non-linear systems that exhibit emergent patterns through self-organization in response to an environmental driving force, and lend themselves to cellular automata (CA) modelling. Through the application of simple rules that describe fundamental processes on a local basis, global patterns emerge. Cellular automata models have been developed to simulate bare-sand environments including sand ripples (Anderson and Bunas, 1993; Werner and Gillespie, 1993; Landry and Werner, 1994) and dunes (Werner, 1995; Momi ji et al., 2000; Bishop et al., 2002), as well as ecological landscapes where typical vegetated patterns emerge based on vegetation presence in neighbouring cells (Feagin et al., 2005; Kéfi et al., 2007), or soil moisture interactions (Esteban and Fairén, 2006). An overview of the use of CA models in ecogeomorphological systems is given in Fonstad (2006). Ecogeomorphological landscapes can be better understood by the inclusion of both geomorphological and ecological processes and the feedback between them (Stallins, 2006), and model analysis may help elucidate processes that impart a greater influence over pattern emergence. A few models incorporate mutual feedback to analyse landscape development in aeolian vegetated environments (de Castro, 1995; Baas, 1996; 2002; Nishimori and Tanaka, 2001). De Castro (1995) used a binary type switch where vegetation presence halted sand transport completely, whereas Baas (1996, 2002) and later Nishimori and Tanaka (2001) varied transport in response to vegetation cover. The 2002 Baas model allowed simulation of bare-sand and vegetated environments and investigation of the influence of different vegetation responses. The research presented here builds upon these earlier investigations, analysing the impact of varying environmental and ecological parameters in detail and considering landscapes where multiple vegetation types are present. The work also includes a more systematic exploration and testing of various technical aspects of the CA algorithm, such as cell polling methods and the issue of implementing oblique winds, and a careful consideration of the parameter ranges in relation to comparative sediment transport fluxes. Our findings in this context can be relevant to bedform cellular automata in general.

Model Description

The DECAL algorithm expands on the original Werner (1995) bare-sand model, which simulates topography composed of stacks of discrete sand slabs on a cellular grid space. Dunes evolve through feedback and local interactions between slabs being moved across the model space in an orthogonal framework (a Von Neumann neighbourhood) with periodic boundaries. We model a closed system with no external sediment sources where the initial sediment thickness represents the maximum volume within the model space that is available to supply transport. Individual slab movements begin with the polling of a grid cell. If slabs are present at the polled cell, the top slab is removed subject to an erosion probability, \(p_e\), and moved downwind a transport length, \(L\), to a destination cell. Deposition at the destination cell is subject to a probability, \(p_d\), and if not deposited the slab is moved another transport length and the process is repeated. Empty (bare) destination cells are assigned lower \(p_d\) values, to emulate the increased saltation distances on hardrock or moist surfaces through more efficient rebound (Bagnold, 1941). In general, \(p_s\) values of 0-6 and 0-4 are assigned to sand-covered and empty cells respectively. We restrict the transport length to one cell-width, \(\ell\) (i.e. to adjacent cells only) to ensure a moving slab cannot pass over, or jump across, intervening local influences, including vegetation (introduced below). The original algorithm allowed variable \(L \geq 1\) to modify overall transport rates, but our research has shown that such an increase in effective slab transport distance is conceptually equivalent to a streamwise dilation of the model space, and does not contribute anything additional to the development of dune patterns.

Besides the elementary transport process, two additional rules govern the movement of slabs in the system during polling. Shadow zones are applied in the downwind lee of topography at an angle of 15° to the horizontal surface, where \(p_e = 0\) (i.e. no erosion) and \(p_d = 1\) (i.e. complete deposition), and avalanching in the direction of steepest descent enforces an angle of
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repose (30° for bare sand). Our research has shown that the inclusion of shadow zones is imperative for the development of recognizable dune forms through the interactions between moving slabs. If this rule is ‘turned-off’ no bedforms develop.

Time is introduced into the algorithm by repetition of the polling events, and the associated time unit of a single iteration, \( I \), is defined as a fixed number of polling events, usually equating to the number of cells in the model space. The sequence and manner of polling influences the frequency that an individual cell is selected over a number of iterations and the polling method appears to influence developing morphology. In polling without replacement, every grid cell is polled exactly once per iteration in a random sequence, whereas in the Werner (1995) model, polling with replacement allows some slabs to remain dormant while others are selected multiple times. Our research has shown that the latter polling method smooths the landscape forms, and so the DECAL algorithm uses polling without replacement to avoid this artificial effect.

The algorithm in the bare-sand mode is capable of replicating desert dune forms as a function of sediment supply and wind regime complexity, comparable to simulation results obtained by Werner (1995) and the reproduction of Wasson and Hyde’s (1983) phase diagram by Bishop et al. (2002), without including the detail of complex airflow or sediment transport dynamics. Simulation of different wind (transport) directions is critical in this respect and can be simulated either directly by changing the direction of slab movement across the grid, or passively by rotating the grid topography under a fixed unidirectional transport. The Werner model directly modelled oblique transport by defining a slab displacement with longitudinal (or streamwise) and transverse (or lateral) components. This approach is limited to a small number of potential discretized oblique directions, fundamentally restricted by the overall length of the displacement vector, and wholly impossible when \( L = 1 \). An alternative is to assign individual slab transport events to either a longitudinal or transverse direction according to probabilities defined by the degree of obliqueness of the desired transport direction. A 60° transport direction, for example, can be simulated by moving one-third of all polled slabs in the ‘longitudinal’ direction, and two-thirds of the polled slabs in the ‘transverse’ direction. However, test simulations show that dunes modelled using this method with a unidirectional wind at an angle oblique to the grid system are more elongated perpendicular to the wind and exhibit unequal horns (Figure 1a), distinctly different from

![Figure 1](image_url)

*Figure 1.* Barchan development from seven initial mounds of sediment, \( h_s = 0.1 \), \( p_d = 0.6 \), under unidirectional wind (indicated by white arrows). (a) Oblique wind modelled using alternating vertical and horizontal movements based on relative probabilities after 300 iterations. (b) Passive method using grid rotation: tessellation of the original landscape that has evolved under initial grid-parallel transport direction after 300 iterations, and selection of rotated grid for new wind direction (white box); (c) resulting rotated landscape with old wind direction indicated, note discrepancies at periodic boundaries; (d) subsequent adjustment of dunes to the new wind direction after a further 100 iterations. This figure is available in colour online at www.interscience.wiley.com/journal/espl
morphologies formed under a transport direction that is parallel to the grid system (Figure 1b). Passive modelling of oblique winds by grid rotation methods also exhibits limitations, however. Bishop et al. (2002) rotated the grid and resampled the morphology, choosing the rotation point to maximize the area retained, and a large model space to minimize the impact of excluding some morphology. We investigated a similar approach, but first tessellate the grid (Figure 1b and c), and use a triangulated irregular network to resample in the central portion of the extrapolated morphology. The tessellation method still excludes some areas of the original model space while repeating others, leading to differences in total sediment volume before and after rotation, requiring the artificial insertion or exclusion of slabs randomly after rotation to balance the volumes. It also destroys the periodic nature of the boundaries, and the space must therefore be sufficiently large to prevent misalignment errors propagating throughout the model space. A possible solution to the sediment conservation problem is rotation of only a circular section of the grid, as implemented by Narteau et al. (2006). Sediment is conserved, but edge effects from where the circular area intersects with the surrounding square model grid can still propagate to the central portion of the model space, particularly during long simulation scenarios with multiple direction changes. Our explorations into different algorithms have not yet resolved the challenge of imposing arbitrary oblique transport directions and the problem remains outstanding. All further simulations reported here are limited to unidirectional transport.

In order to investigate the model’s applicability to real-world situations and its ability to aid in predictions and management of system response to changes in conditions, transport rates in the model must be related to realistic field values and parameter ranges need to be limited. The volumetric flux, \( q \), in the model can be defined as:

\[
q = \frac{Q}{I}
\]

where \( Q \) is the volume of sand transported in dimensions of the fundamental cell-width unit, \( \ell^3/\ell \), derived from the product of \( L \) and the slab height, \( h_s \) (specified as a height in terms of \( \ell \)). Some slabs will travel more than a single \( L \) due to secondary transport in a polling event: a fraction of all slabs in an iteration \( (1 - p_d) \) will travel a second transport length, an even smaller fraction \( (1 - p_d)^2 \), will travel an additional tertiary distance, and so-on; yielding a mean \( Q \) of:

\[
Q = (p_d h_s L)[1 + (1 - p_d) + (1 - p_d)^2 + \ldots + (1 - p_d)^n] = (p_d h_s L)\sum_{n=0}^{\infty}(1 - p_d)^n
\]

The infinite summation is equivalent to \( 1/p_d \), and assuming a flat surface and \( p_e = 1 \), \( q \) becomes:

\[
q = \frac{h_s L}{p_d}
\]

This transport flux can be separated into a volumetric component (conceptually the amount of sediment present in the transport mode/layer), represented by the slab height, \( h_s \), and a speed component (the rate of displacement of this sediment volume, \( u_s \)), represented here by:

\[
u_s = \frac{L}{p_d I}
\]

If \( h_s \) and \( L \) are defined with a physical scale length (m) and \( I \) is defined with a time scale (s), then \( q \) is quantified in \( \text{m}^3 \text{s}^{-1} \) or \( \text{m}^3 \text{m}^{-1} \text{s}^{-1} \) (volume passing across a transverse unit width per unit time) and \( u_s \) is quantified in \( \text{m} \text{s}^{-1} \) (conceptually equivalent to a mean path length per unit time). From Equation 4, the mean path length, \( d_s \), travelled by a slab in a polling event is defined by:

\[
d_s = \frac{L}{p_d}
\]

The assumption of setting \( p_e = 1 \) can now be justified as it is clear that modifying this probability is simply equivalent to (or can be compensated for by) a redefinition of the iteration.

Since \( L \) is set to \( 1 \ell \), the mean path length of a slab is controlled solely by the deposition probability. Test simulations show that at very large mean path lengths the model displays apparent upper-stage planar bed behaviour (Bennett et al., 1998), with low-relief ‘washed out’ bedforms developing when \( p_d \) is very small in comparison to the grid length in the wind direction (Figure 2, top). Under such conditions a slab may travel across the entire grid with very few interactions, essentially bypassing the pattern formation mechanisms. In other cases, mean path length appears to influence the type of bedform that develops (Figure 2, bottom). Using very high \( p_d \) values, conversely, prevents dune formation altogether as the movement of slabs is too restrictive for the system dynamics to develop.
The volume of sediment transported in the system, i.e. $h_s$, must also be limited to an appropriate range in association with realistic transport speeds. Rather than pursuing an analogy with saltation trajectories, we conceptualize slab movement during a wind event as comparable to the propagation of ripples. This seems more appropriate considering the fact that the sand slabs in the model represent sizeable volumes – far removed from individual saltating grains – and since the slabs are not allowed to jump across intervening cells (this would be more suitable for mimicking the saltation process). Working in the Kelso Dunes (California), Sharp (1963) reported ripple celerities, $c$, at different wind speeds, $u$, measured at 1.22 m above the surface and derived a linear relationship (converted to SI units):

$$c = 1.22 \times 10^{-4} u - 7.78 \times 10^{-4}$$

(6)

In order to relate ripple celerity to an overall transport rate we first convert the wind speeds reported by Sharp to estimated shear velocities, $U_*$, using the law-of-the-wall and assuming a roughness length of 0.2 mm, to yield the following derived celerity equation:

$$c = 1.96 \times 10^{-3} U_* - 7.78 \times 10^{-4}$$

(7)

Second, based on the reported sediment grain size of $d = 0.3$ mm, Bagnold’s transport equation (1941) is used to predict transport rates, $q$, for a range of shear velocities, converted to volumetric fluxes assuming a bulk density for sand of 1600 kg m$^{-3}$.

Figure 3 shows the ratio between the ripple celerity (calculated from Equation 7) and the associated volumetric transport flux over a realistic range of shear velocities. This ratio is analogous to the ratio of $u_s$ and $q$ in the model, i.e. $1/h_s$ (note also the dimensional equivalencies). These scaling arguments indicate an upper limit to the appropriate...
range for $1/h_s$ of approximately 13, or, the inverse: a minimum slab height of 0.077. A maximum slab height, meanwhile, is imposed by the desired minimum angular resolution with which slopes can be represented by the stacking of slabs. We suggest an appropriate maximum slab height of 0.13, which allows some variation in modelled slopes by specifying a minimum height difference of four slabs before avalanching is initiated between cells.

Although both $I$ and $\ell$ can be assigned real physical values with respect to the dune environments being modelled, the bare-sand model is fundamentally non-dimensional and therefore can be scaled temporally and spatially to represent either ripples (bedforms) or dunes (landforms). In either case, when unidirectional simulations are run for a sufficient number of iterations eventually all sediment in the model space collects into a single migrating morphology, controlled only by the angle of repose. The wind speed-up factor introduced by Momiji et al. (2000) slows this process but does not ultimately prevent it. The ambiguity of the scale of the bedforms being modelled is in contrast to the clear differentiation between the scales and formation mechanisms of impact ripples versus aeolian dunes (Wilson, 1972; Ellwood et al., 1975). It therefore remains unclear whether the rules represented in the bare-sand CA algorithm relate to fundamental ripple or dune formation processes. As we report below, the inclusion of vegetation in the algorithm establishes a fixed and definite relationship between the temporal and spatial scales by the physiological characteristics of the biotic element being modelled.

**Vegetation**

Ecogeomorphological interactions in the algorithm mimic the effect of vegetation in coastal and semi-arid environments, where vegetation increases the threshold shear velocity required to initiate and sustain transport (Lancaster and Baas, 1998; Kuriyama et al., 2005). This is modelled by modifying erosion and deposition probabilities and the angle of repose at each cell, as a function of its local ‘vegetation effectiveness’, $\rho$, which can be interpreted as analogous to a plant coverage density or frontal area index (FAI). It is a measure of the ability of vegetation on a cell to affect sediment transport, rather than a physical measure of plant biomass. The value of $\rho$ at each cell is adjusted annually, based only on the local sedimentation balance. The yearly cycle is defined in terms of number of iterations. A flow diagram of the model including the vegetation component is presented in Figure 4. When $\rho \geq 0.3$, the angle of repose is increased to 40°, allowing steeper slopes to form on vegetated areas of the model space. The erosion and deposition probabilities are adjusted linearly as a function of $\rho$:

$$p_{e(\text{veg})} = p_{e(bare)} - \rho$$

$$p_{d(\text{veg})} = p_{d(bare)} - \rho(1 - p_{d(bare)})$$

![Figure 3. Relationship between values of $U_*$ and $c/q$ (solid blue line) and the range of appropriate slab heights (1/7.5 to 1/13) for use in the model. This figure is available in colour online at www.interscience.wiley.com/journal/espl](image-url)
where $\rho$ is limited to values within the geomorphically active range $[0, 1]$ that affect transport. The presence of multiple types of vegetation in the model environment is represented by individual $\rho$ values, i.e. a cell may contain one level of vegetation effectiveness for a pioneer grass species (e.g. $\rho_{\text{pioneer}}$) and another for a different level of a successional shrub species (e.g. $\rho_{\text{shrub}}$). Their combined influence on the transport process is based on the sum of their values. Whereas the impact of $\rho$ on erosion and deposition probabilities is limited to the geomorphologically active range $[0, 1]$, the physiological range of $\rho$ depends on species attributes and can extend beyond the geomorphological range to represent a plant’s ability to grow or decline beyond the limits that affect sand transport. When $\rho < 0$, the situation is analogous to nutrient depletion or a hydrologically deficient environment, a dormancy period before seed germination, or the time required to rejuvenate the soil. In the other extreme, $\rho > 1$ suggests a situation where vegetation has grown

**Figure 4.** Flow diagram of the DECAL model. Yellow shaded sequence indicates the algorithm of an individual slab displacement. Green section represents the annual vegetation growth response. This figure is available in colour online at www.interscience.wiley.com/journal/espl
above the density required to shut down transport. It can also represent resilience of an established plant to adverse conditions, a longer lifespan, or the difference between a deep-rooted or shallow-rooted species. It may act as a measure of a plant’s ability to facilitate new seed germination (e.g. Martínez, 2003). The growth or decline of ρ on each cell is assessed annually using growth functions (Figure 5) that reflect the physiological response of the vegetation type to the sedimentation balance (Brown, 1997; Maun and Perumal, 1999; Dech and Maun, 2005). Growth functions capture the differences in tolerance to burial and erosion between vegetation types, as well as the rate at which the vegetation effectiveness can increase annually. Growth functions define different vegetation types that lead to differential colonization of geomorphological niche areas, without the explicit inclusion of interspecies interactions between vegetation types. Growth function characteristics reflect qualitative behaviour of vegetation response to sedimentation described in the literature, however, precise values used in the model were derived by trial-and-error.

Parabolic dunes in the model develop with the combination of two types of vegetation, a pioneer grass and a woody shrub (see below). A pioneer species similar to marram grass (*Ammophila*) or scurf-pea (*Psoralea lanceolata*) requires fresh sediment input for optimum vitality and to stimulate growth (Chadwick and Dalke, 1965; Van der Putten *et al.*, 1993; Moore, 1996; Van der Stoel *et al.*, 2002), and this is captured in the growth function by specifying its peak growth where there is net deposition on a cell, while neutral or negative balances lead to decline due to the impact of soil pathogens and parasites (Maun, 1998). The life cycle of a grass is relatively short compared with a woody shrub and it is more susceptible to changes in environmental conditions, so its physiological range does not extend beyond the geomorphological range. A woody shrub species such as sea buckthorn (*Hippophae*) or juniper (*Juniperus*) can tolerate small changes in sedimentation balance (Dech and Maun, 2006), but prefers a less active landscape and quickly declines when subjected to significant soil erosion or sediment deposition. Its peak growth rate is smaller than the pioneer grass, but once it is established, it is more resilient to environmental change so its physiological ρ range is set to [−0.5, 1.5].

Nebkha dune formation (see below) requires a different growth function that represents vegetation analogous to *Tamarix* or mesquite (*Prosopis sp.*), which can tolerate large sedimentation events in comparison to a pioneer grass or successional shrub (Melton, 1940). Once established, mesquite has a very long lifespan (Bestelmeyer *et al.*, 2006), so its physiological range is larger than a pioneer grass species (Kéfi *et al.*, 2007), typically [−1, 3]. Apart from the physiological and photosynthetic restrictions of a plant’s growth over a yearly cycle, the growth function can be manipulated to reflect the response of similar vegetation types to different climatic conditions. For example, under drought conditions some species of vegetation may grow less vigorously than when moisture is freely available. The growth function can also be manipulated to represent a climate with a shorter growth season and longer response time, to model dunes such as those examined by Hugenholtz and Wolfe (2005b) in Canada. The following sections discuss the manipulation of growth functions and the effects of different sediment supply and transport fluxes on the development of nebkhas and parabolic dune fields.
Nebkha Dune Field Development

The introduction of a vegetation type comparable to *Tamarix* or mesquite induces the development of a nebkha dune landscape, resembling those described by Melton (1940) and Langford (2000). They form in the model under supply-limited conditions from an initial flat, barren surface (Figure 6) with a transport rate of $5 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$, a cell width of 1·25 m and a yearly cycle equivalent to 16 iterations. The dunes exhibit classic deposition tails on their lee side (Hesp, 1981), with shorter windward slopes due to the large size of the vegetation (Hesp, 2002). They are aligned along the dominant wind direction (Tengberg, 1995) and are narrower in width than length (Nickling and Wolfe, 1994; Mountney and Russell, 2006). Vegetation initially grows on incidental sediment accumulation areas, creating a positive feedback mechanism as the vegetation prevents sand from being transported over the new growth, contributing to further vegetation development. The morphology and position of the nebkhas changes little after 10 to 20 simulated years, which agrees with field observations of mesquite dune stability (Bestelmeyer *et al.*., 2006) and formation time-scales in drought affected agricultural land in Mali (Nickling and Wolfe, 1994) and Burkina Faso (Tengberg, 1995). The dune field contains both small, compact nebkhas, and larger complex duneforms, as is observed in mesquite dominated landscapes (e.g. Rango *et al.*, 2000), with sizes generally ranging from 2 to 10 m in length and up to 2·4 m in height, also comparable to field values (Dougill and Thomas, 2002; McGlynn and Okin, 2006). Interestingly, the patch shapes of the vegetation resemble those modelled by Kéfi *et al.* (2007), which relied solely on the relationship between neighbouring plants rather than incorporating geomorphological feedback. This illustrates how interactions between plants and geomorphological processes alone can account for spatial differentiation of species in coastal dune environments, more usually attributed to competition and facilitation among species themselves (e.g. Cheplick, 2005). The resultant nebkha landscape is sensitive to differences in sediment supply and transport flux as well as the relationship between grid size and the size of the vegetation element. These sensitivities are examined in the following sections.

**Sediment supply and transport rate**

In a bare-sand system with unidirectional wind, an increase in sediment supply results in a transition from the formation of barchans to transverse dunes (Wasson and Hyde, 1983; Cooke *et al.*, 1993; Bishop *et al.*, 2002). The initial sediment supply in a semi-arid, vegetated dune system also influences the morphology (Nickling and Wolfe, 1994; Langford, 2000). Model simulations suggest that the evolving morphology depends both on the volume of

![Figure 6.](image-url)
sediment within the system (we model a closed system with no external sediment sources) and the initial vegetation distribution, both of which control the supply of sediment available for transport (Figure 7). Small undulations in the initial morphology produce similar dune fields to an initial flat bed, providing that the overall free sediment volume in the system is conserved. Augmenting the amount of sediment available for transport in the system increases the size of the simulated dunes and changes their shape. Changing vegetation cover, growth rate of encroachment and distribution in the field influence sediment supply and flux (Tengberg, 1995; Hugenholtz and Wolfe, 2005b; Okin et al., 2006). In the model, dune shapes remain consistent, but larger initial vegetation cover decreases sediment supply and dune size (Figure 7 – top row). Nebkha dunes generally form in environments with low sediment supply (Mountney and Russell, 2006). Figure 7 (bottom row) illustrates the changing dune patterns that evolve with an increase in initial sediment base (supply). In a sediment rich, coastal environment, nebkha dunes may initially form (Hesp, 2002), which then initiate the formation of foredunes, and this can also be observed in the modelled landscape with a large sediment base or high sediment supply (transport limited).

Besides sediment supply, dune evolution is also dependent on the transport rates in the environment. The influence of potential sediment flux (Equation 3) and the speed component of this flux (Equation 4) were investigated by modifying either the slab height (to adjust transport rate while keeping speed constant) or the number of iterations defining an annual growth cycle (to change speed, Equation 4, while keeping transport volume constant). The results in Figure 8 (top row) show that nebkha size increases with higher transport rates, concurring with physical observations that nebkhas are non-migratory bedforms that disrupt the sediment flow, trapping sand from an unsaturated saltation system (Mountney and Russell, 2006). Increasing the flux in the model increases the sediment volume moving annually, so more sediment is available to expand dune size. At first, the vegetation can respond positively to an increase in sediment accumulation within its physiological limits, but as landforms develop negative feedback reverses this trend and leads to a decline in vegetation effectiveness.

While transport rates have a marked impact on resultant nebkha forms, changing the speed of the slab transport – while keeping transport flux constant – has little effect on the resulting morphology, as seen in the bottom sequence of Figure 8. The size and distribution of resultant nebkhas do not appear to vary much under a range of speeds (while the overall transport rate is kept constant by adjusting the slab height, Equation 3).

Linking spatial and temporal scales

The introduction of vegetation in the model algorithm destroys the freedom to arbitrarily scale the spatial and temporal dimensions of the simulated landscape. An explicit spatial link between physical vegetation element size and
grid resolution is illustrated by observing differences in nebkha morphology as a function of using different cell sizes. A mesquite-type shrub is generally at least 1 m in diameter (Okin, 2001) and simulations using this type of vegetation produce 2 m to 10 m diameter nebkhas using the standard grid resolution of 1.25 m. Increasing the cell size to 2 m produces similar sized nebkhas but coarsens the resolution (Figure 9, top row). Further reductions of resolution capture a nebkha dune on a single grid cell of 5 m and 10 m, where sediment-covered cells are isolated from each other. Reducing the cell size below the physical size of the represented vegetation element, however, reveals a dramatic breakdown in the expected landform development as the dynamics between the growth function and individual vegetation elements are fundamentally changed. The type of vegetation modelled becomes more akin to a

Figure 8. Nebkha dune formation under varying sediment flux (top) and speed (bottom) conditions compared with the standard conditions used for Figure 6; transport direction left to right. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Figure 9. Simulated morphology using different spatial resolutions ($\ell = 0.4$ m to 10 m, indicated in top-left corner of each panel). The top sequence shows results using a lower resolution than the standard of $\ell = 1.25$ m from figure 6c (shown on the left), the bottom sequence presents results with higher resolutions; transport direction left to right. This figure is available in colour online at www.interscience.wiley.com/journal/espl
small, compact shrub, with the same growth characteristics as mesquite. These virtual plants are able to exceed their physical restraints and grow close together, acting more like a series of sand screens or porous fences that are continuously maintained at maximum effectiveness, trapping sand and forming chevron shaped transverse bars.

The relation between the size of an individual plant and the dimensions of a shadow dune forming in its lee was previously established by Hesp (1981). The above results hint at a more fundamental effect of vegetation as a general control on landform dimensions, going beyond individual shadow dunes. Conceptually, the vegetation imposes a characteristic physical scale on the resultant morphology, unlike the situation for unvegetated dunes which are found over several orders of magnitudes in size (Wilson, 1972), including on other planets with different gravities and atmospheres. Indeed, the bare-sand CA models are fundamentally scale-less, as the spatial and temporal realms are linked only via the transport rate, and the results therefore can be scaled to any spatial or temporal dimension by redefining the cell-size and iteration duration. Incorporating the eco-geomorphological interactions, however, introduces a second separate linkage via the growth response, thus fixing the relation between spatial and temporal domain, and a resultant morphology that is fundamentally controlled by the biotic component. Unlike the absence of a ‘topographic signature of life’ in the context of hillslope erosion suggested by Dietrich and Perron (2006) and the typically fractal-like (hence scale-less) nature of other geomorphological features such as coastlines and river networks (Tarboton et al., 1988), we propose that for aeolian landforms the influence of vegetation, i.e. life, may reveal itself in a characteristic size-range that is fundamentally related to the biological limits of physiological and photosynthetic potential. Such characteristic scaling may be confined largely to aeolian environments, where abiotic geomorphological processes and biological dynamics have comparable power in their interactions, but it may also be evident in other earth surface systems with substantial life components. The relationship between vegetation and dune size is discussed further below.

**Parabolic Dune Development from Blowouts**

The model parameters used to simulate parabolic dune formation in coastal environments differ from those discussed in the previous sections, through the interactions of multiple vegetation species and larger sediment fluxes to develop complex morphologies. A disturbance originating from a decline of vegetation due to adverse localized environmental conditions or anthropogenic impact can lead to the formation of a blowout, which under favourable wind climates may develop into a parabolic dune (Hesp, 2002). The algorithm can simulate the development of parabolic dunes from blowouts in a back dune or continental setting where pioneer grass and woody shrub species coexist (cf. growth functions ‘grass’ and ‘shrub’ in Figure 5). Parabolic dunes form from an initially flat surface, fully vegetated except for five identical, 6-m-wide blowouts (Figure 10). The stochastic nature of the model introduces only minor differences between the overall form of the dunes that develop from the initial blowouts, suggesting that the simple rules are able to consistently replicate the fundamental interactions between sediment transport and ecological control that lead to parabolic dune development.

In the simulations sediment initially builds up downwind of the blowout, until after a few seasons the dynamics of the sand and vegetation begin to align through feedback mechanisms. Grass colonizes the top and lee of the main depositional lobe, which helps to form the classic nose shape and retard the dune movement. This provides the

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**Figure 10.** Parabolic dune development after 50 years (80 iterations per year) from an initial flat, vegetated surface with five identical 6-m-wide blowouts, $\ell = 1.0$ m, $h_s = 0.1$. Green shading indicates pioneer grass $\rho$, size and density of red bars indicate successional shrub $\rho$; transport in three-dimensional view from lower left to upper right. This figure is available in colour online at www.interscience.wiley.com/journal/espl
Parabolic and nebkha dune formation

Table I. Influence of various aspects of the growth function on landscape development (see Figure 5 for vertex labels).

<table>
<thead>
<tr>
<th>Growth function vertices</th>
<th>Effect on landscape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limits of decline (A, E)</td>
<td>Little effect</td>
</tr>
<tr>
<td>Transition between growth and decline (B, D)</td>
<td>Morphology of dunes</td>
</tr>
<tr>
<td>Peak growth rate (C y)</td>
<td>Speed of stabilization</td>
</tr>
<tr>
<td>Optimum sedimentation balance (C x)</td>
<td>Position of vegetation in relation to morphology</td>
</tr>
</tbody>
</table>

required conditions for the shrub type vegetation to colonize the sides and tails of the dune and form trailing arms, typical of hairpin or long-walled parabolic dunes (Pye and Tsoar, 1990; Wiedemann and Pickart, 2004). This also accords well with observations by Arens et al. (2004) that trailing arms were the first areas to be colonized by vegetation after the reactivation of a parabolic dune. Previous attempts to model this type of dune formation with only a single vegetation type were unable to reproduce trailing arms (Baas, 1996). A landscape with a single pioneer species does not develop trailing arms because this type of vegetation does not grow well in stable areas. Conversely, when just a stabilizer species is present in the landscape, vegetation only grows in areas of minor sedimentation change. The magnitude of the peak annual growth of both species under ideal conditions also has an impact on the resultant morphology, where a fast growing shrub is able to stabilize the sediment surface before the transport dynamics of the system have a chance to influence the developing duneforms.

Modifications of the growth function can be used to represent different vegetation types or different environmental and climatic conditions that affect plant vitality. In the DECAL model the growth functions are defined by five vertices (points A through to E in Figure 5). A number of variations on the standard growth functions were simulated to investigate the relative influences of these different aspects of the growth functions on the developing landscape. Our findings are summarized in Table I.

Interspecies competition is not included explicitly in the model – there are no limitations to the cumulative vegetation effectiveness for example – but the two vegetation types are seen to occupy different niche areas with regard to sedimentation conditions as specified by their growth functions. This illustrates emergent ecological behaviour with species growing in different areas or functional zones on the dunes, in similar patterns as those observed in the field (Maun and Perumal, 1999).

The initial blowout size, the amount of sand available for transport and the initial vegetation cover and distribution all affect dune size and shape, both in the field (Hesp, 2002; Hugenholtz and Wolfe, 2006), and in our simulation results. Randomly varying the initial vegetation effectiveness values and distribution of pioneer and stabilizer vegetation produces very different landscapes, as this controls the sediment supply in the system. Parabolic dunes only form when the initial model space is covered predominantly by shrub-type vegetation (Figure 11a and b). Blowouts do not form in the system when the initial shrub coverage is reduced; instead large bare patches exist between vegetated areas, facilitating the development of transgressive ridges. Random undulations on the initial starting surface still result in comparable parabolic dune landscapes (Figure 11c), provided the amount of active sediment available for transport in the initial blowout is sufficient to initiate a migrating depositional lobe.

Figure 11. Simulated landscapes after 50 years developing from flat topography and random initial distributions of vegetation, with $\rho_{\text{shrub}}$ varying from 0 to 0.9 and $\rho_{\text{grass}}$ varying from 0 to maxima of (a) 0.1 and (b) 0.2. (c) Development from initial random topography with blowouts. Yearly cycle of 80 iterations for all simulations, $\ell = 1.0$ m and $h_s = 0.1$. Green shading proportional to $\rho_{\text{grass}}$, size and density of red bars indicate $\rho_{\text{shrub}}$, transport direction from lower-left to upper-right. This figure is available in colour online at www.interscience.wiley.com/journal/espl
Dynamic equilibrium

The interactions between vegetation dynamics and geomorphological sedimentation processes lead to the development of different landscapes that reach various types of equilibrium, depending on plant response characteristics. This is in contrast to bare-sand dunes developing in the original Werner model, where all available sediment ultimately accumulates into a single dune form limited in size only by the angle of repose and the model space boundaries. We carried out a number of simulations to investigate the influence of vegetation characteristics by varying the peak annual growth rates of a pioneer grass ($\rho_{\text{max}} = 0.05 - 0.2$) and a successional shrub ($\rho_{\text{max}} = 0.025 - 0.075$). Equilibrium morphologies that evolve from an initial barren 30 m flat sediment base with a yearly cycle equivalent to 50 iterations are shown in Figure 12a, and range from transverse dunes (scenarios A and B) to parabolic dunes (scenarios E and F). Overall sediment transport activity in the landscape can be monitored by the avalanche frequency as a measure of dune mobility. Figure 12b presents the temporal evolution of landscape activity for a number of simulation scenarios, including those shown in Figure 12a.

**Figure 12.** (a) Planform equilibrium morphologies after 80 decades for selected growth function combinations A – F (peak annual growth values (vertex C in Figure 5) are detailed in 12b, all other vertices are the same as Figure 5). The morphology of growth function combinations G and H are similar to B and D respectively. Successional shrubs reside in interdune and stabilized areas and grass is present on the lee slopes of mobile dunes, similar to depictions in Figures 10 and 11. (b) Trends of avalanche number per iteration, indicative of landscape activity, for various peak growth rates of pioneer and successional vegetation species over an extended simulation period. All simulations start from an initial 30-m-deep flat bed with no vegetation, using a yearly cycle of 50 iterations, $\ell = 1.0$ m and $h = 0.1$. This figure is available in colour online at www.interscience.wiley.com/journal/espl
Vegetation response during the initial stages of landscape evolution is slower than the sediment transport processes. This results in an initial lag or reaction time, where small mobile transverse ridges form irrespective of specific vegetation response, before the feedback mechanisms begin to affect subsequent development. Vigorous vegetation (E and F) may overpower dune migration and eventually result in a static equilibrium state consisting of relict or fossilized parabolic dunes (Figure 12a, E and F), with dune size dependent on precise vegetation characteristics. This is evident by the larger parabolic dunes that form in scenario E, where shrub growth is more conservative. Moderate vegetation vitality leads to the development of dune fields that appear to attain a dynamic equilibrium around a steady landscape activity (D and H), where vegetation dynamics and sediment transport processes are comparatively balanced. The pathway of landscape mobility towards equilibrium for weaker vegetation (B and G) can be chaotic. In these scenarios vegetation is continuously buried by sediment and the system is sensitive to minor instabilities that may initiate a transition to a different equilibrium state. An example of this can be seen in the mobility trend of G, where between 60 and 80 decades a breakdown in vegetation facilitates the merging of two transgressive ridges.

The conceptual impact of vegetation on landscape form was highlighted in a previous section. The above results further illustrate the inherent ability of vegetation to impart a characteristic length scale in aeolian environments. The scenario simulations also indicate that the combination of multiple vegetation types and their growth responses relative to one another affect the evolutionary sequences, sensitivity of the landscape and potential equilibrium states.

Conclusions

The DECAL model is capable of simulating realistic looking vegetated dune development in coastal and semi-arid environments, including nebkha and parabolic dune fields. These landforms develop as a result of interactions between multiple vegetation types and sediment transport processes, modelled by simple, local rules in a cellular automaton algorithm. The addition of vegetation links spatial and temporal scales, in contrast to bare-sand scaleable models where it is unclear whether ripples or dunes form. Qualitative evaluations of ecogeomorphological scenarios show that the emergent behaviour conforms to our current understanding of dune system response to changes in sediment supply and flux as well as impacts of different vegetation types and distributions. Investigations outlined in this paper demonstrate a fundamental link between ecological components and abiotic geomorphological processes, where dune size and shape are controlled by vegetation characteristics, resulting in various types of evolutionary trajectories and (dynamic and static) equilibrium landscapes. This simple vegetated dune model illustrates the power and versatility of a cellular automaton approach for exploring the effects of interactions between ecology and geomorphology in complex earth surface systems.

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