Global and Planetary Change 64 (2008) 76–92

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response

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ARTICLE INFO

Article history:
Received 1 August 2008
Accepted 2 October 2008
Available online 17 October 2008

Keywords:
aeolian features
landform evolution
cellular automata
self-organisation
environmental effects
parabolic dunes

ABSTRACT

Aeolian dune field development in coastal and semi-arid environments is a function of complex ecogeomorphic interactions which are sensitive to fluctuations in climatic and environmental conditions. We explore the relationships between ecological and geomorphic processes in the development of these landscape patterns and speculate on their response to variations in vegetation vitality and sediment transport capacity, indicating possible consequences of climate and land use change, using the Discrete ECogeomorphic Aeolian Landscape (DECAL) cellular automaton algorithm. This algorithm models dune field behaviour that reflects long-term trends prevalent in palaeo-records, but also elucidates possible evolutionary progressions, relaxation period sequences and threshold sensitivities. The landscape response is sensitive both to the perturbation itself and the state of the system when the disturbance occurs. Response amplitude decreases in simulated systems with reduced mobility unless an external disturbance mimicking fire or land clearance is applied concurrently with a reduction in growth vigour triggering a threshold type response when sufficient vegetation is removed. The model demonstrates that the relative response characteristics of the multiple vegetation types and their mutual feedback with geomorphic processes impart a significant influence on landscape equilibrium or attractor states. Fast growing vegetation enables the formation of hairpin (long-walled) parabolic dune systems, which eventually become sediment starved and stabilise, whereas inhospitable conditions inhibiting vegetation growth contribute to the development of active transgressive transverse dune fields. This simple vegetated dune model illustrates the power and versatility of a cellular automaton approach for exploring thresholds, sensitivities and possible evolutionary trajectories associated with the interactions between ecology, geomorphology and climatic conditions in complex earth surface systems.

1. Introduction

Aeolian vegetated dune fields in coastal and semi-arid environments evolve and adapt to changes in wind regime and vegetation cover through complex ecogeomorphic interactions, forming recognisable, self-organised patterns if the conditions persist over a long period of time. Hairpin or long-walled parabolic dunes with trailing arms are common in stabilising vegetated dune environments, whereas in more active, sparsely vegetated systems, transgressive transverse or broad-lobe parabolic dunes dominate (Pye and Tsoar, 1990; Wiedemann and Pickart, 2004). Vegetation is highly sensitive to changes in climate, available nutrients and sedimentation conditions, and its colonisation rate can determine whether a landscape will become stabilised or reactivated. Evidence suggests that both local and regional factors play an important role in landform development, for example the local curtailing of agricultural practices in Israel has led to the stabilisation of dune fields that still remain active in nearby regions of Egypt (Tsoar and Blumberg, 2002; Levin and Ben-Dor, 2004; Levin et al., 2007; Yizhaq et al., 2007). Similarly, where vegetation growth is restricted by saline or low fresh water availability or sediment supply is very high, transverse and barchanoid dunes form in preference to parabolic dunes (e.g. Barbosa and Dominguez, 2004; Mason et al., 2004; Marín et al., 2005; Rose, 2006). Other local disturbances may include the formation of a blowout on a stabilised dune, due to fire or vegetation clearance (e.g. Arens et al., 2004; Arens and Geelen, 2006), initiating the development of a parabolic dune and local reactivation. On a broader, global scale, changes in climate may affect dune development directly by modifying wind regime or indirectly by influencing vegetation cover and sediment supply (Lancaster, 1997). Palaeoclimatic field evidence indicates that during warmer, drier climatic episodes in the Holocene, active dune fields were dominant in areas that are now regarded as stable (e.g. the Great Plains, USA and Canada (Muhs et al., 1997; Arbogast and Johnson, 1998; Forman et al., 2001; Clarke and Rendell, 2003; Mayer and Mahan, 2004; Wolfe et al., 2006), northern Gulf of Mexico coastal plain (Otvos,

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doi:10.1016/j.gloplacha.2008.10.002

2004) and central Poland (Goździk, 2007)). Climate change has the ability to alter hydrological conditions, modifying both climate variability and moisture availability (Overpeck and Cole, 2006), which affect vegetation growth. It is likely that future changes in climate will create the conditions necessary to activate or stabilise large areas of sensitive aeolian environments (Thomas et al., 2005) and modelling can help indicate possible future trends (Thomas and Wiggs, 2008; Viles et al., 2008) and explain historical system dynamics.

Long-term dynamics and response of aeolian ecogeomorphic landscapes to changes in land use, climate and environmental forcing are not well quantified (Lancaster, 1997) in comparison to unvegetated desert dune dynamics (e.g. Wasson and Hyde, 1983), and have typically been investigated using conceptual models (e.g. Tsoar, 2005; Hugenholtz and Wolfe, 2005a; Yizhaq et al., 2007), remote sensing observations (e.g. Kutiel et al., 2004; Thomas and Leason, 2005; Marín et al., 2005; Levin et al., 2007), or through the use of mobility indices (e.g. Ash and Wasson, 1983; Lancaster, 1988) that relate potential dune activity to the ratio of potential transport capacity (wind energy — erosivity) and sediment mobility (vegetation cover — erodibility) (e.g. Muhs and Holliday, 1995; Bullard et al., 1997; Wolfe, 1997; Lancaster and Helm, 2000; Knight et al., 2004). These indices are successful in emulating medium to long-term trends, but have difficulties representing annual variation due to an inability to accurately account for response lag (Lancaster and Helm, 2000), and the relaxation period that follows when the balance between ecological and geomorphic processes is shifted. This response lag is defined as the period before the reaction to a perturbation is evident and occurs due to changes in vegetation and geomorphic temporal response. Dune dynamics may remain unaffected for a period of time during adverse conditions because even though vegetation mortality is high, roots and decaying plant matter continue to affect transport potential (Mangan et al., 2004). Likewise, similar lag periods are observed when conditions improve because finite vegetation growth response controls the point at which it begins to influence transport patterns (e.g. Hesse and Simpson, 2006). Lag periods are common after a perturbation is applied in a geomorphic system and are generally followed by a relaxation phase, where feedback between internal components allow the system dynamics to move towards an equilibrium or attractor type state, given sufficient time and constant forcing. Hesse and Simpson (2006) found field evidence of response lags in both vegetation and dune mobility to positive and negative climate perturbations. Systems may also exhibit resilient tendencies, whereby the effect of a change in conditions is absorbed for a period of time until a threshold is attained and the system behaviour moves towards a new equilibrium state (Brunsden and Thornes, 1979; Brunsden, 2001).

Dune fields may be treated as dissipative nonlinear systems that exhibit emergent patterns through self-organisation 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. CA 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; Momiji et al., 2000; Bishop et al., 2002). A number of models also incorporate mutual feedback between geomorphic and ecological processes (de Castro, 1995; Baas, 1996; Nishimori and Tanaka, 2001; Baas, 2002, 2007; Baas and Nield, 2007; Nield and Baas, 2008; Durán et al., in press), which play an important role in landscape development (Stallins, 2006). These types of models have the ability to aid in our understanding of dune field construction, ecogeomorphic feedback and response to perturbations (Wiggs, 2001; Fonstad, 2006; Tooth, 2007). Baas and Nield (2007) built upon an earlier single species model (Baas, 1996, 2002) by considering multiple vegetation types and investigated the influence and interactions of these, simulating realistic nebkha and parabolic dune behaviour under different sediment supply and potential transport capacity conditions. Modelling allows us to investigate theoretical medium- and long-term ecogeomorphic trends and system resilience by comparing numerous realisations under varying conditions to examine the inherent landscape behaviour and response to perturbations, which is not possible with limited field data. The application of simple fundamental principles allows us to elucidate possible evolutionary progressions, threshold sensitivities and comparable magnitude and duration of disturbance response, and link these to qualitative field observations and trends, improving our understanding of system dynamics (Phillips, 2004, 2006). Our research utilises the Discrete ECogeomorphic Aeolian Landscape (DECAL) model to examine the internal mechanics of the system response to changes in growth and sediment transport potential by considering changes in mobility and vegetation coverage. It highlights the ability of this type of model (Huntley et al., 2006; Coulthard et al., 2007; Murray, 2007), to aid in our understanding of complex system behaviour and feedback mechanisms, and indicate landscape transformations that may occur due to changes in climatic and environmental conditions. In this paper we examine aeolian landscape behaviour at a medium temporal and spatial resolution, simulating the evolution of the nonlinear system behaviour towards an end-member signature state, or attractor, in response to perturbations.

2. Model description and method of landscape analysis

We explore ecogeomorphic landscape evolution under a unidirectional wind regime, using a CA algorithm that extends inclusion of a vegetation component (Baas, 1996, 2002) into the original bare-sand cellular automaton model (Werner, 1995), where discrete sand slabs self-organise into topographic landforms on a Van Neumann neighbourhood cellular grid with periodic boundaries. A detailed description of the algorithm can be found in Nield and Baas (2008). Dunes evolve through feedback and local interactions between geomorphic and ecological processes, where repeated slab transport across the model space is governed by deposition probabilities, 15° shadow zones in the lee of topography prevent erosion and incur 100% deposition of moving slabs, and avalanching enforces the angle of repose (30°). Vegetation is incorporated via a 'vegetation effectiveness' value, ρ, which affects transport (by altering erosion and deposition probabilities, p_e and p_d) and angle of repose (increased to 40° when $\rho \geq 0.3$), and can be interpreted as analogous to a plant coverage density or frontal area index (FAI). It represents the ability of vegetation on a cell to influence the threshold shear velocity required to initiate and sustain sediment transport (Lancaster and Baas, 1998; Kuriyama et al., 2005), rather than a physical measure of plant biomass and may include the significant influence of litter cover (e.g. Wiggs et al., 1995), as well as roots and dead matter. This biomass was postulated by Mangan et al. (2004) to contribute to the lack of reactivation of the Great Plains during the 1930's drought and has been observed by Arens and Geelen (2006) in accelerating the stabilisation of artificially destabilised dunes in the Netherlands.

The impact of ρ on p_e and p_d is limited to the geomorphically active range [0,1], whereas the physiological range of ρ depends on species attributes and can extend beyond the geomorphic 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, a hydrologically deficient environment, a dormancy period before seed germination, or the time required to rejuvenate the soil. In the other extreme, $\rho>1$ implies a situation where vegetation has grown 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.

Feedback is included in the model by annual adjustment of ρ based on the sedimentation balance of a cell over the previous year, where a year is defined as a fixed number of iterations that can be varied to