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Parabolic dunes and their transformations under environmental and climatic changes: Towards a conceptual framework for understanding and prediction

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ABSTRACT

The formation and evolution of parabolic aeolian dunes depend on vegetation, and as such are particularly sensitive to changes in environmental controls (e.g., temperature, precipitation, and wind regime) as well as to human disturbances (e.g., grazing, agriculture, and recreation). Parabolic dunes can develop from the stabilisation of highly mobile barchan dunes and transverse dunes as well as from blowouts, as a consequence of colonisation and establishment of vegetation when aeolian sand transport is reduced and/or when water stress is relieved (by increasing precipitation, for instance). Conversely, existing parabolic dunes can be activated and may be transformed into barchan dunes and/or transverse dunes when vegetation suffers environmental or anthropogenic stresses. Predicted increases in temperature and drought severity in various regions raise concerns that dune activation and transformations may intensify, and this intensification would have far-reaching implications for environmental, social, and economic sustainability. To date, a broad examination of the development of parabolic dunes and their related transformations across a variety of climate gradients has been absent. This paper reviews existing literature, compares data on the morphology and development of parabolic dunes in a comprehensive global inventory, and scrutinises the mechanisms of different dune transformations and the eco-geomorphic interactions involved. This knowledge is then integrated into a conceptual framework to facilitate understanding and prediction of potential aeolian dune transformations induced by changes in environmental controls and human activities. This conceptual framework can aid judicious land management policies for better adaptations to climatic changes.

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1. Introduction

Desertification and associated land degradation in dry regions are responsible for increased emission and reduced sink of atmospheric carbon, currently accounting for about 4% of global emissions (Lal, 2001; Millennium Ecosystem Assessment, 2005). Land degradation and vegetation loss also result in a severe reduction of global food production (Scherr and Yadav, 1996). Projections of future climatic change, in particular increases in temperature and drought severity and decreases in freshwater availability expected in various regions around the world (Maestre et al., 2012; IPCC, 2013), raise concerns that aeolian activity and desertification may be exacerbated by more active dune transformations, particularly the activation of dunes that are currently stabilised by vegetation and/or biogenic crusts (Forman et al., 1992; Muhs and Maat, 1993; Le Houérou, 1996; Muhs et al., 1996; Lancaster, 1997; Thomas and Leason, 2005; Thomas et al., 2005; Ashkenazy et al., 2012). Relatively small changes in climatological parameters may contribute to an abrupt change in vegetation cover and catastrophic shifts between states of eco-geomorphic systems (Muckersie and Shepherd, 1995; Lavee et al., 1998; Rietkerk et al., 2004; Sole, 2007; Yizhaq et al., 2007; Yizhaq et al., 2009; Bhiry et al., 2011).

Despite a growing awareness of the great sensitivity of aeolian landforms to vegetation change as well as the diverse feedback between vegetation and sand erosion and burial, the complex eco-geomorphic interrelations between vegetation and dune landforms are not completely understood. Parabolic dunes, in particular, are common aeolian landforms that are strongly controlled by eco-geomorphic interactions. Such dunes often form where there is an adequate sand supply, a unidirectional wind regime, and a moderate vegetation cover (Hugenholtz et al., 2008; Hugenholtz, 2010; Lancaster, 1995; McKee and Bigarella, 1979). Under ameliorating vegetation conditions, parabolic dunes can develop from highly mobile non-vegetated dunes such as barchan dunes and transverse dunes (Tsoar and Blumberg, 2002; Reitz et al., 2010; Hart et al., 2012; Hesp and Walker, 2013). When the vegetation cover decreases, however, parabolic dunes can be transformed back to highly mobile, non-parabolic dunes (Hack, 1941; Anton and Vincent, 1986). The development and transformations of parabolic dunes are also highly sensitive to changes in many environmental factors such as precipitation (Landsberg, 1956; Stetler and Gaylord, 1996), temperature (Wolfe and Hugenholtz, 2009), and wind strength and variability (Hesp, 2002; Tsoar et al., 2009), as well as to changes in land management and other anthropogenic factors (Hesp, 2001; Tsoar and Blumberg, 2002). A brief discussion on the distribution, morphology and change of parabolic dunes was recently provided by Goudie (2011), but there has been no detailed examination of the differences in development of parabolic dunes and their related transformations on a global scale across a wide climatic gradient.

This paper reviews past research on parabolic dunes and their related transformations on a global scale, exploring mechanisms of different dune transformations and their indications in the context of climatic changes, mediated by vegetation, which is then integrated into a conceptual framework of understanding and predicting dune transformations influenced by changes in environmental variables and human activities. Analysis of dune landform transformations within a conceptual framework allows for the examination of eco-geomorphic responses to environmental fluctuations and climatic changes on different temporal and spatial scales. This analysis also provides a better understanding of different dune transformation mechanisms and possible dunefield evolutions, and provides a framework for planning judicious land management practices.

2. Morphology, development, and migration of parabolic dunes

Simple parabolic dunes are U- or V-shaped dunes in plan with two trailing arms pointing upwind, a deflation basin contained within arms, and a depositional lobe at the downwind end (Pye and Tsoar, 1990; Hesp and Walker, 2013). Vegetation, usually shrubs or trees, surrounding the parabolic dunes can resist widening of the deflation basins, whilst plants on the trailing arms can bind sand and maintain the parabolic shape of dunes. Many parabolic dunes have a slip face, and some large ones may have multiple crests and slip faces. As the airflow approaches towards the dune crest, flow is compressed by the stoss slope, resulting in the increases in shear stress and sediment transport. Beyond the crest, flow expands and may create a separation zone within which positive pressure causes reversal of flow back up the lee slope, forming ‘back-eddies’ (Walker and Nickling, 2002; Delgado-Fernandez et al., 2013). In the zones of flow separation, flow deceleration causes grainfall deposition which forms grainfall lamination on slip faces (Hunter, 1977). As deposition continues, avalanching occurs where the slope angle reaches the critical angle of repose. The resulting grainflow and sand flowage change pre-existing stratification and form cross-strata (Hunter, 1977; Hugenholtz et al., 2007).

Parabolic dunes can exhibit variable morphologies (Cooke et al., 1993; Kilibarda and Blockland, 2011) (Fig. 1), governed by wind regime, sediment supply and local vegetation characteristics (Hack, 1941; Wasson and Hyde, 1983; Rubin and Hunter, 1987; Pye, 1990; Baas, 2007; Hugenholtz, 2010).

Elongated parabolic dunes with long-walled arms, also referred to as hairpin- or U-shaped dunes, develop in a strong unidirectional wind regime, whereas a greater directional variability results in much shorter trailing arms and imbricate dune forms (Pye, 1982; Pye, 1983c; Tinley, 1985; Gaylord and Dawson, 1987; Hesp and Walker, 2013). Crosswinds that blow oblique to the prevailing wind may lead to left- or right-handed asymmetry in dune morphology. Where multiple discrete wind directions dominate at different times, hemicyclic- or digitate-shaped parabolic dunes may form (Filion and Morisset, 1983; Pye and Tsoar, 1990). The seasonal variations of winds also significantly influence airflow patterns and sediment transport over dunes (Byrne, 1997; Hansen et al., 2009).

Relatively abundant sediment supply is crucial for dunes to maintain their mobility and grow in height. The availability of external sediment supply from sandy beaches and foredunes largely controls the size of coastal dunefields (Aren et al., 2004). As dunes move forward, they can also grow in height by incorporating sand from their substrata underneath (Livingstone and Warren, 1996). If dunes move onto a non-sandy substratum in the absence of an external sediment supply, the depositional lobes may flatten gradually due to continuous sand loss.

The ecological conditions and characteristics of the regional vegetation are the other essential factors determining the morphology of parabolic dunes. Digitate parabolic dunes are usually associated with the presence of a forest cover, as trees force dunes to move in divergent directions and facilitate the formation of high depositional lobes with steep windward and lee slopes (Filion and Morisset, 1983; Buynevich et al., 2010; Levin, 2011). If a regeneration of the tree population is interrupted (by wildfires, for example), digitate parabolic dunes can further transform to hemicyclic dunes (Filion and Morisset, 1983). Long-lived perennial shrubs may also play an important role in trapping sediment, developing into nebkhas, and maintaining the shape of parabolic dunes (Tsoar and Blumberg, 2002; Hesp, 2008). Ephemeral annual plants, however, can only anchor dune surfaces temporarily and suffer abrupt changes under external pressures (e.g., precipitation, temperature and grazing intensities), and therefore exert minimal impacts.

Migration of parabolic dunes is principally controlled by the interplay between sand drift potential imparted by wind regime, moisture content and vegetation cover (Bagnold, 1941; Fryberger, 1979; Ash and Wasson, 1983; Lancaster, 1997; Lancaster and Baas, 1998).

The orientation of coastal parabolic dunes is largely determined by wind regime (Landsberg, 1956; Jennings, 1957), which is usually defined in terms of sand drift potential, reflecting the capacity of winds to transport sediment, as an index of regional wind energy (Fryberger, 1979; Wasson and Hyde, 1983; Arens et al., 2004; Tsoar, 2005; Levin et al., 2006; Levin, 2011).