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Complexity confers stability: Climate variability, vegetation response and sand transport on longitudinal sand dunes in Australia's deserts

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ABSTRACT

The relationship between antecedent precipitation, vegetation cover and sand movement on sand dunes in the Simpson and Strzelecki Deserts was investigated by repeated (up to four) surveys of dune crest plots (≈25 × 25 m) over a drought cycle (2002–2012) in both winter (low wind) and spring (high wind). Vegetation varied dramatically between surveys on vegetated and active dune crests. Indices of sand movement had significant correlations with vegetation cover: the depth of loose sand has a strong inverse relationship with crust (cyanobacterial and/or physical) while the area covered by ripples has a strong inverse relationship with the areal cover of vascular plants. However, the relationship between antecedent rainfall and vegetation cover was found to be complex. We tentatively identify two thresholds; (1) >10 mm of rainfall in the preceding 90 days leads to rapid and near total cover of crust and/or small plants <50 cm tall, and (2) >400 mm of rainfall in the preceding three years leads to higher cover of persistent and longer-lived plants >50 cm tall. These thresholds were used to predict days of low vegetation cover on dune crests. The combination of seasonality of predicted bare-crest days, potential sand drift and resultant sand drift direction explains observed patterns of sand drift on these dunes. The complex vegetation and highly variable rainfall regime confer meta-stability on the dunes through the range of responses to different intervals of antecedent rainfall and non-linear growth responses. This suggests that the geomorphic response of dunes to climate variation is complex and non-linear.

1. Introduction

Vegetated sand dunes are widespread in the deserts and desert margins of all continents except Antarctica. They are often the foundation of commercial or subsistence grazing economies in drylands. The response of vegetated dunes to future climate change has been investigated using model scenarios of future climate state and empirical relationships between average climate, dune vegetation and sand transport (Knight et al., 2004; Thomas et al., 2005; Yizhaq et al., 2009). However, the response of arid land vegetation to climate on both climatic (seasonal – multi-decadal) timescales, and timescales of sand transport events (seconds – days), is poorly described (Nano and Pavey, 2013) and the effect of vegetation on sand transport rates is based on a limited body of empirical data (e.g. Kuriyama et al., 2005; Lancaster and Baas, 1998).

Longitudinal sand dunes present an additional complex set of conditions, with variable wind strength (Wiggs et al., 1996), wind direction and vegetation cover over the dune surface. Wiggs et al. (1995) found an exponential relationship between dune surface mobility and exposed (non-vegetated) surface area as well as a complex distribution of sand mobility over the dune surfaces. This is consistent with observations of the climate parameter M (the ratio of frequency of strong winds to the effective precipitation at a site) (Lancaster, 1988), describing dune mobility, driving variations in sand transport, modified by lags in vegetation response (Lancaster and Helm, 2000). Bullard et al. (1997) also found that M is variable on inter-annual to decadal timescales and proposed that this variability results in fluctuations in dune activity in the Kalahari Desert.

Drought has been proposed as a disturbance which may result in activation of dunes (Forman et al., 2006; Mangan et al., 2004) by reducing protective plant cover. A recent study of the impacts of the prolonged drought in the Israeli dunes (Siegal et al., 2013) concluded that although vegetation cover had been reduced dramatically, following a lag of some years, the dunes were unlikely to become active because of the persistent biological crust. By contrast, a further study (Kidron et al., 2017) found that biological crust was degraded and ruptured during drought by complex inter-

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actions with mobile sand areas. These results highlight the importance of both the degree and duration of drought (Mangan et al., 2004), as well as the complexity added by diverse flora (Nield and Baas, 2008).

There are other important drivers of vegetation change on sand dunes. Tsoar and others (Thomas and Tsoar, 1990; Tsoar and Møller, 1986) have described how the removal of vegetation by over-grazing has led to widespread activity of Sinai dunes, separated by a national border from well-vegetated and largely stable dunes where grazing is currently restricted in Israel. Fire is also another vegetation disturbance factor which has been proposed as a driver of sand dune activation (Barchyn and Hugenholtz, 2013). Fires in Australian desert dunefields have been documented to reduce covering vegetation for years (Levin et al., 2012; Strong et al., 2010). In the eastern Simpson Desert, fire area has been shown to have a complex relationship with antecedent rainfall and drivers of rainfall variability (Greenville et al., 2009). However, none of these studies have documented sand transport or dune activity following fires and the effectiveness of fire in driving dune activation has been questioned because of this lack of evidence (Barchyn and Hugenholtz, 2013).

However, the role of vegetation as a driver of dune activity or passive response is disputed. For example, a recent model of dune activation (Yizhaq et al., 2007, 2013) proposes that the transition from dunefield activity to stability and back, is dependent on wind strength, and that dune stabilization occurs through wind velocity relaxation. Certainly, wind strength has long been linked to sand transport rates (Bagnold, 1941) and sand transport has also been shown to be proportional to vegetation cover (Kuriyama et al., 2005; Lancaster and Baas, 1998), however the extent to which wind limits plant growth is not well known. Models of dune evolution which incorporate vegetation (Duran and Herrmann, 2006; Nield and Baas, 2008) utilise growth functions partly dependent on wind-driven sand transport rates but also with growth 'vigour' manipulated to achieve the effects of dry or wet periods (Nield and Baas, 2008; Bel and Ashkenazy, 2014).

The actual impacts of drought on vegetation can be very severe at ecosystem scales (Ponce Campos et al., 2013) and landscape scales (Nano and Pavey, 2013). However, this response has been found to be complex and non-linear (Reynolds et al., 2004). Rainfall frequency and amount are important in determining plant growth response (Schwinning and Sala, 2004). The pulse-reserve model (PRM) suggests that a pulse of resources (precipitation) will produce a growth response (reserve) if there is sufficient rainfall to increase soil moisture and sustain growth for each plant functional type. Some rainfall events are ineffective if they are either too small or not followed by further rain (Fernandez, 2007; Nano and Pavey, 2013).

Around 2000, much of eastern Australia entered a long drought (the 'Millennium Drought') which lasted until it was broken by a strong La Niña event in 2010 (Gergis et al., 2012; Timbal and Fawcett, 2013; Wardle et al., 2013). The extreme 'Millennium Drought' provides an opportunity to test the response of vegetation and sand transport over the most extreme range of climate variability in Australia in the modern era. In this study, we present the first analysis of dune vegetation response over an entire decadal drought cycle.

Together with data from Hesse and Simpson (2006), additional surveys from Simpson and Strzelecki sites in 2005 and 2012 are used to analyse (1) the response of sand mobility to vegetation cover, and (2) the response of vegetation on dunes to precipitation, to better understand how dunes respond to climatic variability, (3) over both the drying and wetting phases of a drought cycle. This study aims to better understand the responsiveness of desert dunes to climate forcing, specifically the role of vegetation cover and crust in limiting the availability of transportable sand. Assumptions regarding the response of vegetation cover to climate change underlie the interpretation of sand dunes as proxy indicators of past climate where alternative sources of palaeoclimate proxy data are limited (Thomas and Burrough, 2012).

2. Field sites and methods

In this study, sand dunes within the Strzelecki Desert dunefield (Della, Bosca and Teilta dunes) and Simpson Desert dunefield (Mayan and Aztec dunes) were investigated (Fig. 1; Table 1). The sites have been described previously (Hesse and Simpson, 2006). Dunes in each area are longitudinal, tending to dendritic in the Strzelecki, and are composed of medium red sand with very low clay content, in contrast to some source-bordering dunes in the same dunefields (Wasson, 1983). The Simpson Desert dunes (Mayan and Aztec) are around 20 m high, spaced around 1 km apart separated by broad flat interdunes with exposed cay-rich sediment and some pans. Both dunes and interdunes are well vegetated, generally, but there is a strong zonation of vegetation according to substrate and elevation on the dunes so that the dune crests are usually the least well-vegetated parts of the landscape and with a distinctive species composition. The Strzelecki Desert dunes (Della, Bosca and Teilta) are less well organized (more junctions and terminations, wavy crests), smaller (8–10 m) and more closely spaced (≈300 m). The dune crests share many of the characteristics of the Simpson dunes, including the plant species, but the interdunes have a different character (more rounded) and vegetation (different shrub and tree species).

The field area is one of moderate to low wind energy (Kalma et al., 1988). Ashkenazy et al. (2012) derived DP over Australia from 6 hourly observational data (NCDC) according to the method of Fryberger and Dean (1979). Although much of the Simpson and Strzelecki was an area of no data, areas to the southwest had DP values in excess of 250 vector units (intermediate energy environment of Fryberger and Dean) while areas to the northeast had DP less than 200 (low energy environment). The overall pattern is of declining sand transport potential towards the centre of the continent.

The Mayan and Della sites were chosen in 2002 to be 'representative' of their areas, in which dunes were largely vegetated and lacking mobile slip faces. However, there are bare areas of active sand movement, usually restricted in area and to the dune crests, throughout the dunefields including on dunes neighbouring Mayan and Della sites. In 2004 the Aztec (neighbouring Mayan) and Bosca (neighbouring Della) sites were selected to measure vegetation and sand dynamics on these bare areas as a comparison with the vegetated crest sites (Mayan and Della). At each site quadrats were established on the narrow crests and surveyed up to four times between 2002 and 2012 in winter or spring (Table 1). Quadrats were also measured on the flanks of Della and Mayan dunes in 2002 only (Table 1). In 2002 and 2004 total station surveys were made of each crest quadrat at 1 m intervals.

Weather observations from Bureau of Meteorology automatic weather stations (AWS) at Birdsville and Moomba were used to derive time series of several climatic variables. In addition, older observer-based stations nearby were used for long-term precipitation statistics only (Table 2). AWS records of 3-hourly wind speeds and directions, and daily maximum gust were utilised. The 3-hourly records of wind speed and direction were used to calculate the total sand drift potential (DP), resultant sand drift potential (RDP) and resultant drift directions (RDD) following a modification of the method of Fryberger and Dean (1979). With access to highly accurate metered observations it was decided not to bin observations into velocity or direction classes. The units are thus not com-