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Interactions among hydrological-aeolian processes and vegetation determine grain-size distribution of sediments in a semi-arid coppice dune (nebkha) system

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ABSTRACT

The formation of coppice dunes (nebkhas) has been attributed to both aeolian and hydrological processes, however, the interactions between these processes and vegetation dynamics are poorly understood. Additionally, a systematic study on the roles of dune geometry, morphology and hydrological processes in relation to sediment grain-size distribution in the coppice dune system is lacking. Here, we analyzed detailed grain-size distribution and saturated hydraulic conductivity for sediments collected from a series of coppice dunes with different morphological features and phases of development in a degraded shrubland in the southwestern US. Our results show that fine-grained dune sediments are associated with the wind-driven accumulation of very fine sand and fine sand (50–250 μm), irrespective of the height of the dunes. Patterns of grain-size distribution are strongly related to the relative positions along the dune-interdune system and the alignment with the dominant wind direction. Thus, the current notion that dune sediments contain more sand and less silt than interdune soils is over-simplistic. The fact that the grain-size distribution and the saturated hydraulic conductivity are heterogeneous for the dune-interdune system with different morphological features suggests that the relative contributions of aeolian and hydrological processes are distinct in the evolution of coppice dunes.

1. Introduction

Coppice dunes, also termed nebkhas or nabkhas, are sand dunes that form around vegetation. Coppice dunes have been reported in many parts of the world (e.g., Dougill and Thomas, 2006; Kidron and Zohar, 2016; Langford, 2000; Tengberg, 1995; Wang et al., 2006). Coppice dunes are often associated with areas having degraded soil and vegetation resulting from anthropogenic disturbances. Case in point is the coppice dune formation resulting from woody shrub encroachment into native grasslands throughout the arid and semi-arid regions of southwestern US and globally (e.g., Gibbens et al., 2005; Nickling and Wolfe, 1994; Okin et al., 2001; Schlesinger et al., 1990; Tengberg, 1995; Wang et al., 2006). The formation of coppice dunes and the subsequent redistribution of soil resources have important implications for local pastoral economies, sediment transport, topography, and biodiversity (D'Odorico et al., 2012; Gillette and Pitchford, 2004; Rango et al., 2000; Ravi et al., 2007). In these landscapes, information on the formation, structure and growth of coppice dunes can provide distinct clues about regional climate-vegetation feedbacks and environmental changes (Du et al., 2010; Okin, 2013). Furthermore, rapid changes in formerly stable coppice dune patterns can be considered as indicators of land degradation or desertification in drylands (Langford, 2000; Nickling and Wolfe, 1994; Tengberg, 1995). Hence, to effectively assess and control desertification resulting from vegetation change it is critical to understand the coppice dune dynamics.

While the formation of coppice dunes requires a vegetation type that withstands burial of its roots and branches by sediments, other exogenic mechanisms are also involved. Most studies have stressed the role of aeolian processes, including the erosion of sediments and their deposition under the shrub canopies (Langford, 2000; Lang et al., 2013; Nickling and Wolfe, 1994). Other studies attribute the formation of coppice dunes to sediment-laden runoff (Buis et al., 2010; El-Bana et al., 2002; Eldridge and Rosentreterand, 2004), based on the notion that runoff originating from bare soil interspaces converges towards the dunes thereby leading to the deposition and accumulation of nutrient-rich sediments beneath the canopy. Ravi et al. (2007) proposed a conceptual framework to highlight the hydrological controls on coppice dune initiation, which suggests that sediment-laden runoff may also occur from the top of the mounds to edges due to the lower infiltration capacity under the shrub canopy. However, this study focused on

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sediment mounds with height < 0.3 m, and the role of hydrological processes on the formation of large coppice dunes (e.g., height > 1 m in their study area), particularly on the spatial distribution of grain size, is still unknown.

The interactions between vegetation and various abiotic processes may lead to heterogeneities in the sediment grain-size distribution within a dune. Existing literature on the grain-size distribution of sediments within a dune and at the interdune spaces is inconsistent. However, the cause of this discrepancy is not clear. For instance, many studies have shown that dune sediments contain more sand and less silt and clay than interdune soils as a result of the additions of saltating sand particles driven by wind (e.g., Hennessy et al., 1985; Nickling and Wolfe, 1994). Langford (2000) and Ravi et al. (2007), however, showed that sediments at the interdunes contain significantly more sand than those within the dunes. These studies, however, generally overlook the variation of sediment grain size at different positions of the dune, and in particular their relative positions to the prevailing wind (i.e., upwind versus downwind or perpendicular versus parallel to wind). In addition, saltation happens to a wide range of particles (50–500 μm) that are primarily concentrated at the height < 1 m (Field et al., 2010; Li et al., 2007). Coppice dunes with height > 1 m will also be able to capture fine suspension particles (i.e., < 50 μm).

The fact that particles with different size may move with different modes in the atmosphere suggests that dunes with different height and morphological features may display different characteristics in grain-size distribution. A recent study at the Jornada Experimental Range of southern New Mexico (USA) suggests that the content of fine sand (100–250 μm) is higher in dune sediments than that of interdune soils, but the relative abundance of sediment particles between dune and interdune positions may be affected by the morphology of the dunes (Li et al., 2017).

Here, we analyzed detailed grain-size distribution for sediments from a series of coppice dunes with various size and morphology in a wind-susceptible environment in the Chihuahuan Desert, southern New Mexico, United States. The objectives of the study were to: 1) characterize the detailed grain-size distribution of coppice dune sediments for a series of dunes with various morphological (i.e., size and height) features, 2) distinguish the role of aeolian and hydrological processes that are responsible for the movement of a wide spectra of particle sizes in the sediment, and 3) develop a conceptual model of coppice dune dynamics in relation to aeolian and hydrological controls. We hypothesized that saltation is responsible for particle addition for small dunes whereas suspension is more important for large dunes (i.e., height > 1 m), and the accumulation of fines at the edge of the dunes is the result of the downslope movement of sediment-laden overland flow on the dunes.

2. Methods

2.1. Site description

The study was conducted at the USDA-ARS Jornada Experimental Range (JER) in the northern Chihuahuan Desert, 35 km northeast of Las Cruces, New Mexico. This area has a mean annual precipitation of 247 mm and an average potential evapotranspiration of 2300 mm per year (Gibbens et al., 2005). At the JER, nearly 80% of the erosive winds occur from a southwesterly direction, and dominant wind erosion events happen during early March to May (Helm and Breed, 1999). In the past 150 years, marked transitions of vegetation from grassland to honey mesquite (*Prosopis glandulosas*) shrubland and dunes have occurred in this area (Gibbens et al., 2005). The mesquite-dominated dune systems are primarily located in the northern part of the JER, where the coppice sand dunes have height up to a few meters. More detailed description of the dune systems in this area may be found in Rango et al. (2000) and Langford (2000).

Table 1
Characteristics of the coppice dunes measured in this study.

Dune classification	Dune morphology (m)[a]				Estimated age (yr)[b]	Number of sediment samples
	Perimeter	Height	Length (major axis)	Width (minor axis)		
Large (n = 2)	33.5 (2.1)	2.8 (0.4)	14.5 (0.7)	5.5 (0.7)	100	71
Medium (n = 3)	19.0 (2.6)	1.3 (0.2)	7.0 (1.0)	5.3 (1.2)	30	81
Small (n = 5)	8.1 (4.3)	0.5 (0.2)	2.8 (1.4)	2.3 (1.6)	< 10	85

[a] Values are means and standard deviations in parentheses.
[b] The age of the dunes was estimated according to Graham Gadzia and Ludwig (1983).

2.2. Experimental methods

Field measurements were conducted in June 2016. A total of 10 mesquite coppice dunes were randomly selected with the consideration that they are largely isolated from neighboring dunes to avoid the interdune effect (Table 1, Fig. 1). These dunes are generally elongate and aligned parallel to the dominant wind direction. For each dune, we measured length (major axis, parallel to prevailing wind), width (minor axis, perpendicular to prevailing wind), height, and the perimeter of the dune around the base. The height of the dunes was measured from the base of the dune to the center of the mesquite canopy, which typically protrudes about 0.3–0.75 m from the dune.

The mesquite dunes selected for this study were further classified based on the height of the dunes into large (height ≥2 m), medium (1 m ≤ height < 2 m), and small dunes (height < 1 m). For each dune, dune and interdune sediment sampling was conducted along two transects: parallel and perpendicular to the prevailing wind (Fig. 1). For the transect parallel to the prevailing wind, distance along the transect was always measured from the interdune at the upwind side. The transect extended half-way into the interdune spaces to the adjacent dune. Soil and sediment sampling was conducted on the top 5 cm of the soil (interdune) or sediment (dune), and litter was carefully excluded. Sediments or soils were sampled every 1 m for large and medium dunes, and 1 m or 0.5 m for small dunes. The location of the sediment and soil samples in relation to four microsites, i.e., interdune, edge, dune, and dune top along the transects were also recorded (Fig. 1a). A total of 237 soil and sediment samples were collected for grain-size analysis.

2.3. Laboratory analysis

In the laboratory, all sediment samples were air-dried and sieved using a 2-mm sieve. Sediments were further split into approximately 20 g subsamples using a riffle sampler (Humboldt Mfg. Co. IL, USA) for grain -size analysis. The grain size of the sediment samples was determined using a laser diffraction particle size analyzer (LS 13320, Beckman Coulter, Inc. CA, USA), which measures the size distribution of soil particles suspend in liquid or air using the principles of light scattering. The LS 13320 with the tornado dry powder system measures particle size distribution of samples in dry powder form (suspended in air), which is ideal for aeolian sediments compared to wet dispersion. The system has a dynamic grain size measurement range of 0.4–2000 μm.

2.4. Data and statistical analysis

We reported the mean and sorting of grain size using the graphical methods of Folk (1968). In this method, the grain-size statistical parameters are given in the phi unit (Φ), which is a logarithmic transformation of millimeters into whole integers. While mean is the average grain-size, sorting (σ) is a measure of the grain-size variation of a