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Sediment transport and wind flow around hummocks

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ABSTRACT

This study presents field-based observations demonstrating the relationships between vegetation density, shear stress, and sediment transport surrounding hummocks. Data collection for 120 min measured wind velocities using a sonic anemometer, grain impacts from four miniphones (MICs) deployed on and to the side (in unobstructed flow) of a hummock, trap-derived sand transport, and hummock vegetation densities between 3–26%. These data provide the parameters to estimate model-based transport rates from Bagnold, Zingg, Kawamura, and Lettau and Lettau, and to use the Bagnold slope correction equation. The average trap- and co-located MIC-based transport rates were 25.0 and 89.8 g/m^2/s with an R^2 of 0.39 ($p < 0.01$). Linear regression analysis comparing model-estimated and trap-based transport was significant ($p < 0.05$) using the Kawamura and Lettau and Lettau models. The highest correlation between modeled and observed transport rates from the MICs and the trap was found using the Zingg and Bagnold models, though all four models were statistically significant ($p < 0.05$). Correcting the Bagnold transport model using his slope correction equation did not substantially change the R^2 value ($p > 0.05$). A positive relationship between vegetation coverage and transport rate was observed. The strongest correlation between vegetation coverage and transport rate was found when considering the two MICs placed on the hummock within the vegetation. The MIC placed adjacent to the hummock had a low R^2 that was statistically insignificant ($p > 0.05$). These findings suggest that flow steering around the hummock side and grain projection around and over the hummock plays an important role in hummock morphology and processes.

1. Introduction

This study investigates sediment transport around a hummock in a coastal environment. Previous studies have included hummocks in their discussion of larger dune processes (Hesp and Thom, 1990). To the best of our knowledge, this is the first study to observe transport conditions surrounding this specific aeolian landform.

Numerous models have been formulated to quantify sand transport rates in ‘ideal’ conditions (i.e., flat surface, uniform grain size, free of vegetation and crusts); however, none truly account for the extremely variable, non-ideal conditions ubiquitous to coastal dune environments (Davidson-Arnott and Law, 1990; Sherman et al., 1998; Bauer et al., 2009). These transport rate models have shown to behave with “mixed to poor results” when compared to empirical observations. For example, Sherman and Hotta (1990) conclude that transport rate models, including Bagnold (1937) and Lettau and Lettau (1978), perform poorly mainly because of discrepancies resulting from non-ideal, yet natural, conditions such as heterogeneous topography and the presence of vegetation. Yet, relatively few studies have quantified the nature of the relationship between sand transport and these natural variations (e.g., Arens et al., 2001; Hesp et al., 2005; Kuriyama et al., 2005). Therefore, this study aims to measure transport and wind flow surrounding a hummock with various vegetation densities and to test the performance of four transport models against empirical observations.

2. Background

2.1. Hummocks

A hummock is a small dune, sometimes referred to as a hillock or coppice dune (Pye, 1983; Hesp and Thom, 1990). Relatively few studies have focused on hummocks and their processes compared to other aeolian landforms. Some studies have included hummocky dunes in their description of field sites or in their consideration of other process morphologies (Pye, 1983; Hesp and Thom, 1990; Elliot et al., 2000). To the best of our knowledge, no study has exclusively discussed hummock morphology and no field study

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has investigated transport on hummocks, this study focuses on the latter.

'Hummock,' as a term, is used in several sub-fields of geomorphology including aeolian geomorphology, glacial geomorphology, and stratigraphy (Gudjonsson, 1992; Elliot et al., 2000; Thullen et al., 2005; Keefe et al., 2010). Pye (1983) classified hummocks as impeded dunes. Their migration is blocked by surface roughness factors, such as vegetation, and they tend to remain stable for longer time periods compared to transgressive dunes. Hesp and Thom (1990) propose that hummocks, which they call coppice dunes, are formed by a "chaotic" assemblage of vegetation colonizing a deflation basin or a sand flat and may lead to the growth of an incipient foredune. In some cases, a foredune ridge may not be more than "an irregular series of adjacent [hummocks] separated by depressions and incipient blowouts" (Pye, 1983).

Migration of hummocks occurs when salt-blasted windward vegetation dies and new shoots grow in the lee; the newly exposed sediment is entrained and deposition occurs in the wind shadow of the incipient vegetation. This process relies on prolonged exposure to transport and typically occurs in sandy environments with well-sorted grains and patchy colonizing plant life (Hesp and Thom, 1990). Elliot et al. (2000) suggest that the relationship between morphology and vegetation for hummocks can be extrapolated to larger scales that may support sand management applications in arid environments.

2.2. Modeling transport

Sherman et al. (1998, 2012) compare empirical observations with predicted estimates of mass transport using the Bagnold (1937), Kawamura (1951), Zingg (1952), Kadib (1965), and Lettau and Lettau (1978) models. Shear velocity, which can be estimated using the Law of the Wall equation, is a common parameter to these models. Sherman et al. (2012) replaced the von Kármán parameter (κ) with the apparent von Kármán parameter (κ_a) in the Law of the Wall equation to improve the equation's estimation of shear velocity. It is standard practice when measuring wind velocity (e.g., when using cup anemometers) to use the Law of the Wall equation; however, this calculation is not needed if using a sonic anemometer. Table 1 shows four transport rate models and their associated correlation coefficients (C) used by Sherman et al. (1998, 2012) to compare observed and model-derived transport rates (Eqs. (1)–(4)). In Sherman et al. (1998), the Bagnold and Zingg models performed the best with least square values (R^2) of 0.37. Using the apparent von Kármán parameter in the Law of the Wall equation improved the statistical agreement of all model predicted and observed transport rates, with Lettau and Lettau performing best ($R^2 = 0.71$) when forcing the least-squared line through the axes origin (Sherman et al., 2012). However, even under this 'best case scenario,' an R2 of 0.71 still lends itself for plenty room for improvement.

Modeling aeolian transport presents challenges because of non-ideal conditions found in natural environments, such as variability of the surface slope and of the wind field. Furthermore, the models assume a homogeneous transport field, however, significant transport variability has been documented (e.g., Bauer and Sherman, 1993; Namikas, 1999; Baas, 2008). One of the difficulties with modeling transport is slope; the aspect and angle of the surface over which sediment is transported greatly affects transportation and deposition. For example, it takes more energy to transport grains up a windward slope than down the lee of a dune. Bagnold (1973) found that applying a correction coefficient (G) to his modeled transport rates (Eq. (1)) helps correct for the effects of slope:

$$G = \frac{tan\alpha}{cos\theta(tan\alpha + tan\theta)} \tag{5}$$

where α is the angle of internal friction for the sediment, assumed to be 32°, and Θ is the surface slope. Bagnold's correction coefficient is multiplied by the modeled transport rate to yield a slope-corrected estimate of transport.

Another factor affecting model accuracy is surface roughness, or any element (e.g., plant or sand fence) that disrupts the wind flow. Vegetation typically reduces wind velocity and alters the roughness length encountered by the flow (Burri et al., 2011). From the earliest empirical studies (Olson, 1958) to the most recent experiments (Burri et al., 2011), nearly all observations have shown a negative relationship between vegetation density and sediment transport. For example, Buckley (1987) found that an 8% vegetation cover corresponds with a reduction in transport in excess of 50%. Lancaster and Baas (1998) observed a 90% reduction in sand transport with a 12% vegetation cover compared to bare sand.

The variability of natural vegetation covers presents difficulties in both measuring and predicting sediment transport. Many previous studies investigating the impact of vegetation on transport were performed in arid environments or in laboratory-based wind tunnels; coastal environments present more difficulties for measuring and predicting transport, especially compared to the latter. Arens et al. (2001) found that a 10 m span of 9.1% vegetation coverage on a foredune reduces transport by nearly 99%. Over the same distance with 2.3% vegetation cover reduces transport by 80%. Kuriyama et al. (2005) observed a 50% reduction in transport through vegetation coverage of nearly 20% on a beach. Both Arens et al. (2001) and Kuriyama et al. (2005) found that transport decreases significantly at a "critical" density of vegetation. Meanwhile, Lancaster and Baas (1998) observed after an initial precipitous drop, transport rates leveled out at higher vegetation

Table 1
Sand transport models considered by Sherman et al. (1998, 2012).

Model		Observed v. Modeled q R^2	
		Sherman et al., 1998	Sherman et al., 2012
Bagnold (1937) (Eq. 1)	$q = C(\frac{\rho}{g})u_*^3\sqrt{(\frac{d}{D})}$ $C = 2.8$ (naturally graded sand)	0.37	0.45
Kawamura (1951) (Eq. 2)	$q = C(\frac{\rho}{g})(u_* - u_{*t})(u_* + u_{*t})^2$ $C = 2.78$	0.35	0.59
Zingg (1952) (Eq. 3)	$q = C(\frac{d}{D})^{\frac{3}{4}}\frac{\rho}{g}u_*^3$ $C = 0.83$	0.37	0.41
Lettau and Lettau (1978) (Eq. 4)	$q = C\sqrt{(\frac{d}{D})}\frac{\rho}{g}(u_* - u_{*t})u_*^2$ $C = 4.2$	0.31	0.71

ρ is fluid density; g is acceleration due to gravity; d is median grain size; u_* is shear velocity; ρ_s is grain density; D is reference grain diameter (0.25 mm); u_{*t} is threshold shear velocity.