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A simple method to estimate threshold friction velocity of wind erosion in the field

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[1] This study provides a fast and easy-to-apply method to estimate threshold friction velocity (TFV) of wind erosion in the field. Wind tunnel experiments and a variety of ground measurements including air gun, pocket penetrometer, torvane, and roughness chain were conducted in Moab, Utah and cross-validated in the Mojave Desert, California. Patterns between TFV and ground measurements were examined to identify the optimum method for estimating TFV. The results show that TFVs were best predicted using the air gun and penetrometer measurements in the Moab sites. This empirical method, however, systematically underestimated TFVs in the Mojave Desert sites. Further analysis showed that TFVs in the Mojave sites can be satisfactorily estimated with a correction for rock cover, which is presumably the main cause of the underestimation of TFVs. The proposed method may be also applied to estimate TFVs in environments where other non-erodible elements such as postharvest residuals are found. **Citation:** Li, J., G. S. Okin, J. E. Herrick, J. Belnap, S. M. Munson, and M. E. Miller (2010), A simple method to estimate threshold friction velocity of wind erosion in the field, *Geophys. Res. Lett.*, *37*, L10402, doi:10.1029/2010GL043245.

1. Introduction

[2] Wind erosion is a highly nonlinear, threshold-controlled process. A crucial parameter in wind erosion is the threshold friction velocity (TFV), which controls both frequency and intensity of erosion events [*Marticorena et al.*, 1997]. Threshold friction velocity is the minimum friction velocity required to initiate movement of soil particles, representing the strength of forces among soil particles and capacity of an aeolian surface to resist wind erosion [*Batt and Peabody*, 1999; *Shao and Lu*, 2000]. Nearly all wind erosion and dust flux models require the specification of TFV [*Shao et al.*, 1993; *Marticorena and Bergametti*, 1995; *Okin*, 2008]. However, determining TFV in practice is difficult and the results may be unreliable because the soil's threshold friction velocity is affected by a number of factors, such as soil texture, soil moisture, rocks, salt, surface crusts, and the distribution of vegetation or other roughness elements [*Shao and Lu*, 2000; *Belnap et al.*, 2007].

[3] Following the pioneering and classic works of *Bagnold* [1941] and *Owen* [1964], numerous experimental (e.g., wind tunnel experiments and field observations) and modeling (e.g., theoretical and empirical) studies have been conducted to determine threshold friction velocities for soils with different characteristics [*Raupach et al.*, 1993; *Marticorena and Bergametti*, 1995; *Shao and Lu*, 2000; *Dong et al.*, 2002; *Ravi et al.*, 2004; *Cornelis et al.*, 2004; *Ravi and D'Odorico*, 2005; *Belnap et al.*, 2007]. Despite an extensive database on soil movement as a function of soil and associated plant characteristics, most current experimental and modeling methods have limited applications in the field. The use of a field wind tunnel, although able to provide benchmark of TFVs against which other methods can be compared, may fail to account for the high spatial heterogeneity of soil, as well as the impact of roughness elements in wind erodible arid and semiarid environments. In addition, both wind tunnel and field measurements are labor-, time-, and cost-intensive, therefore, placing a practical limitation on their applications to experiments at regional and global scales. Modeling methods, on the other hand, mostly focus upon the analysis of forces exerted on soil particles. Model inputs are normally derived from wind tunnel experiment with assumptions that soils are uniform, spherical particles resting over a dry and bare surface [e.g., *Bagnold*, 1941; *Owen*, 1964; *Shao and Lu*, 2000]. Therefore, such models may be not appropriate to field conditions where soil and roughness elements are heterogeneous and usually contain multiple grain sizes and shapes that vary in grain density and packing. This limitation may be particularly pronounced if numerous TFVs are required for large-scale experiments. Field studies have shown that TFVs are very sensitive to disturbance and the degree of physical and biological soil crusting [*Marticorena et al.*, 1997; *Belnap and Gillette*, 1997; *Belnap et al.*, 2007]; hence models based on soil texture or soil particle distribution may be not applicable to predict threshold friction velocities for disturbed soils, as a disturbance (e.g., trampling) may result in the change of TFVs but not soil texture or particle shape.

[4] In this study, we present a physically-based, fast, and easy-to-apply method to estimate threshold friction velocities that works for both bare and protected surfaces. We first examined consistent patterns between threshold friction velocity measured in wind tunnels and a variety of field methods to identify the optimum method or combined methods for estimating TFV. Then we tested whether the proposed method was able to provide satisfactory estimates of TFV in other environmental settings. The method presented in this study allows estimates of TFV in support of quantitative modeling of aeolian flux using a set of easily-obtainable field data. This method could potentially be

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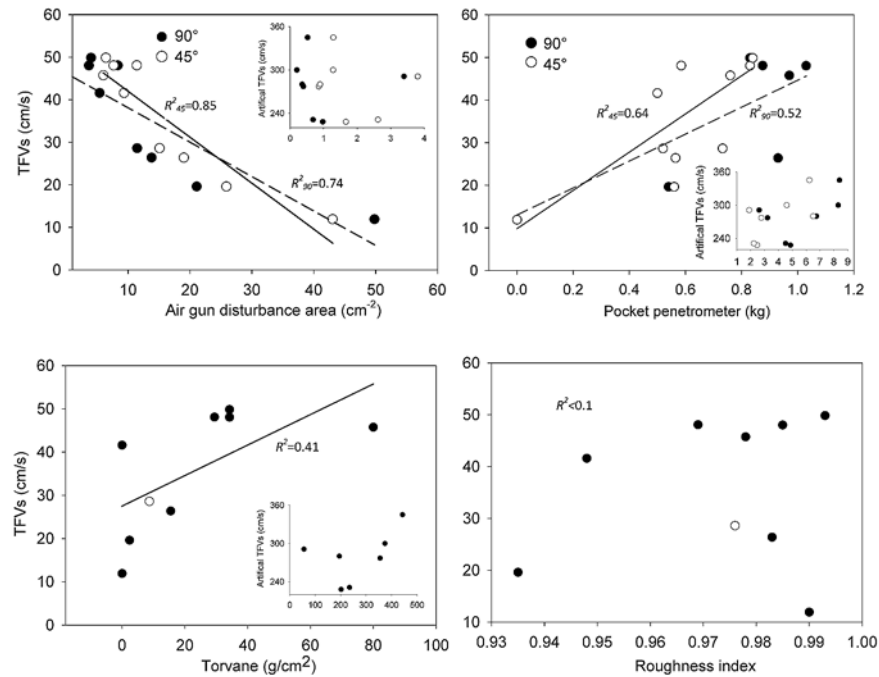[4]Southeast Utah Group, National Park Service, Moab, Utah, USA.

Figure 1. The relationships between threshold friction velocity (TFV) and measurements of air gun, pocket penetrometer, torvance, and roughness chain in Moab sites. The inset graphs show the tests where TFVs were not reached and artificial TFVs were designated as the friction wind speed obtained from the actual wind profiles. Note the air gun data (90°) for one of the TFV reached sites was missing and penetrometer reading on sandiest site was zero for both 45° and 90°.

included in standard National Resource Inventory field methods to improve national-wide monitoring of soil vulnerability to wind erosion.

2. Experimental Methods

[5] Our primary study site was located on lands adjacent to Moab, southeastern Utah. The study area has dispersed shrub cover (e.g., *Sarcobatus vermiculatus* and *Atriplex canescens*), with a mix of perennial (e.g., *Stipa comata and Hilaria jamesii*) and annual grasses (e.g., *Bromus tectorum*) in the shrub interspaces. Field experiments were conducted in summer 2009 on a wide variety of soil types from clay loam (~25% sand) to nearly 100% sand. Biological and physical soil crusts were frequently present in the study area.

[6] A portable, open-bottomed wind tunnel was used to estimate TFVs using methods described by *Marticorena et al.* [1997] and *Belnap et al.* [2007]. The working section for the wind tunnel was 150 mm × 150 mm and 2.4 m in length. The tunnel used a 5:1 contraction section with a honeycombe flow straightener and a rough conical diffuser attached to the working section. Wind speed data were measured twice using a pitot tube at eight heights spaced approximately logarithmically apart from 0.1 cm above the surface to 10.16 cm. The threshold wind speed was defined as the velocity at which fragments were initially detached from the soil surface. Threshold friction velocity was reached in 9 out of 16 tested sites. We estimated the resistance of the soil surface to wind erosion at each site with several instruments, including an air gun, pocket penetrometer, torvane, and roughness chain. Ten to fifteen replicate measurements were taken prior to the wind tunnel test with each of the instruments within 5 m of the wind tunnel's

footprint. A 760 Pumpmaster air gun, shooting spherical copper projectiles with a diameter of 4.5 mm and cross-sectional area of 0.2 cm², was fired at the surface with a muzzle height of 15 cm at angles of 45° and 90° relative to the soil surface. The air gun was pumped three times for each application, which resulted in a muzzle velocity of ~146 m/s. The air gun was equipped with multiple safely controls and other safety precautions such as eye protection were also exercised during the field experiment. The soil surface disturbances created by the projectiles were typically elliptical in shape and the dimensions of maximum diameter and a line perpendicular to the maximum diameter were recorded. Pocket penetrometers (QA Supplies, FT011) that measure the resistance of the soil surface to compressional force were also applied at 45° and 90° angles to the soil surface. A penetrometer measurement was recorded when the soil surface was impacted. The torvane measures the shear strength of the soil surface and was applied at 90° to the soil surface. Finally, a 20 cm metal chain was applied on the soil surface and the length of the chain required to span on roughness elements was recorded. The roughness of the soil surface (≤1.0) was designated as the ratio of the chain's length on the rough surface relative to its original length.

[7] In addition to the Moab sites, we also revisited a number of sites in the Mojave Desert near Barstow, CA, where soil threshold friction velocities were measured in 2003 using the same wind tunnel [*Belnap et al.*, 2007]. Field measurements were conducted based upon the preliminary experimental results of the Moab sites. Sites in the Mojave Desert were typically dominated by *Larrea tridentata* and *Ambrosia dumosa* with sparse perennial grasses in the shrub interspaces. Contrary to the Moab sites, rocks (>2 mm, by size class) were found at nearly all the sites. Rock cover was

Table 1. Multiple Linear Regression Models That Best Predict TFVs (cm/s) in Both Moab and Mojave Desert Sites[a]

		Predictors					
Site	Intercept	Air Gun (cm^2)	Penetrometer (kg)	Rock Cover (%)	R^2	P	RMSE (cm/s)
Moab	4.095	−0.078	0.191	-	0.90	<0.001	4.52
Moab+Mojave	3.267	−0.063	1.206	0.011	0.91	<0.001	15.1
Moab+Rock cover[b]	23.20	−0.078	0.191	1.54	0.45	<0.01	24.4

[a]Note TFVs were log-10 transformed.
[b]Mojave sites only.

measured over the wind tunnel's footprint prior to wind tunnel runs using a line-intercept method across 1 m transects [*Belnap et al.*, 2007]. In both the Moab and Mojave Desert sites, soils had an estimated moisture content <3% when field experiments were conducted.

[8] Wind profiles in the wind tunnel were fit to the law of the wall according to *Marticorena et al.* [1997]:

$$U = \frac{u*}{k}\ln\frac{z}{z_0}$$

where U is mean wind speed at height z, k is von Karman's constant (set to 0.4), $u*$ is friction velocity, and z_0 is aerodynamic roughness height. The relationships between selected testing methods and TFVs were determined using Spearman's rank-order correlation and linear regression of log-transformed TFVs against the ground measurements. Finally, multiple linear regressions were performed to identify the optimum combination for TFV estimates, and the quality of the estimation was characterized by values of R^2 and root mean square errors (RMSE).

3. Results and Discussion

[9] Measured threshold friction velocities fell in the range of 10–50 cm/s for crust-free or slightly crusted soils in Moab sites, but they were not reached using our wind tunnel on the sites when either physical or biological crusts were well-developed (Figure 1), suggesting these sites have TFVs greater than 50 cm/s. Figure 1 further shows that soil TFVs were negatively related to the surface area of the dis-

turbances created by the air gun and were positively related to the measurements of pocket penetrometer and torvane, suggesting that the greater the soil's resistance to disturbance the higher the TFVs. The disturbances created by air gun were generally smaller when applied at 90° relative to 45°. For those sites where TFVs were not reached, the disturbances were substantially smaller than 4 cm^2. For one site the disturbance was as small as 0.25 cm^2 (only slightly larger than the projectiles) and the surface sustained disturbance up to 8 kg (penetrometer) or 440 g/cm^2 (torvane). This site was dominated by clay with well developed physical crusts, suggesting that such sites are highly resistant to wind erosion. In contrast, maximum disturbance sizes were found on the sandiest site with an average size of nearly 50 cm^2, corresponding to a TFV as low as 12 cm/s. Both air gun and penetrometer methods applied at 45° showed more pronounced relationships with TFVs than those of at 90°, and they were both superior to torvane and roughness chain measurements. Indeed, the torvane method failed to give readings on crust-free sites, and the roughness chain method was not significantly related to TFVs.

[10] Multiple linear regression analyses including all field measurements showed that TFVs in the Moab sites were best predicted using the combination of air gun and pocket penetrometer methods, both applied at 45° ($R^2 = 0.90$, RMSE = 4.5 cm/s (Table 1 and Figure 2)). The application of this empirical equation to the Mojave Desert sites, where air gun and penetrometer measurements were conducted, however, systematically underestimated TFVs, when compared to wind tunnel measurements ($R^2 = 0.64$, RMSE = 66.8 cm/s).
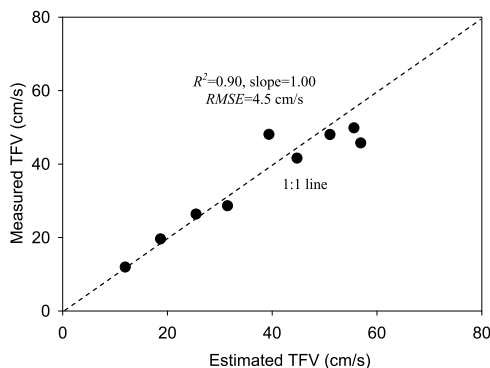

Figure 2. Comparison between measured and estimated threshold friction velocities (TFVs) based on the combination of air gun and pocket penetrometer measurements in Moab, Utah sites. RMSE is the root mean square error of estimation (cm/s).
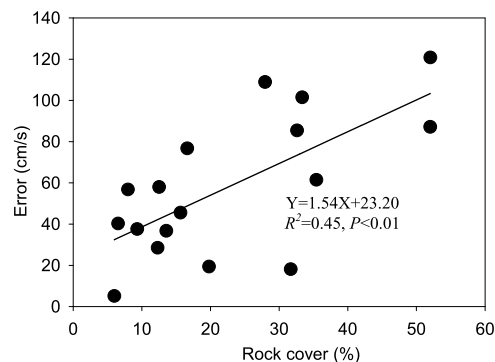

Figure 3. Relationship between rock cover and TFV errors at the Mojave Desert sites. Errors were calculated as the difference between the actual TFVs and predicted TFVs using the air gun and penetrometer measurements as shown in Table 1.
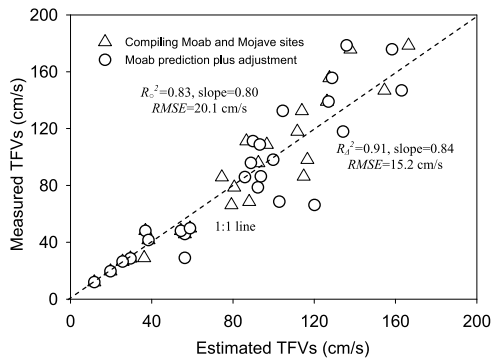
Figure 4. Comparison between measured and estimated threshold friction velocities (TFVs) for both Moab and Mojave Desert sites using different methods. In the first method ($\triangle$), data from both Moab and Mojave were directly compiled; in the second method ($\circ$), TFVs in the Mojave sites were predicted using the Moab equation but were corrected by the relationship between rock cover and estimation errors. RMSE is the root mean square error of estimation (cm/s).

[11] Threshold friction velocities in the Moab sites were substantially lower than those of the Mojave Desert sites. *Belnap et al.* [2007] have pointed out that rock cover in the Mojave Desert may substantially affect soil's susceptibility to wind erosion and cause high TFVs. Rock cover in the Mojave Desert sites varied from 30–90%, but only rocks in the size range of 2–4 mm (8–52%) were significantly positively related with TFVs ($R^2 = 0.25$, $P < 0.04$). Nevertheless, rock cover was positively and significantly correlated with errors calculated as actual TFVs measured at the Mojave Desert minus predicted TFVs using only air gun and penetrometer measurements in the relationship derived at the Moab sites (Figure 3). This suggests that rock cover is a main cause of the underestimation of TFVs in the Mojave sites. Including the rock cover data to estimate the degree of underestimation when only the Utah equation (utilizing only air gun and penetrometer measurements) was used (Table 1) resulted in a significant prediction of measured TFVs, with an RMSE of 20.1 cm/s (Figure 4). This is not as low as the RMSE obtained in the regression method that compiles all data from the Moab and Mojave sites (Table 1 and Figure 4), but it is a remarkable improvement over the simple application of the Moab regression to the Mojave sites (RMSE = 66.8 cm/s).

[12] It should be noted that our visit to the sites at the Mojave Desert was based on GPS coordinates obtained in 2003. It is likely that for some of the sites we were not able to locate the exact spots where wind tunnel was tested. Considering the high spatial heterogeneity of soil properties in desert soils, possible site disturbance thereafter, and the time that had elapsed since the wind tunnel measurements, the quality of TFV prediction in the Mojave sites exceeded our expectation. Not all wind erodible environments have the presence of rocks. Other non-erodible elements such as woody debris in desert shrubland and postharvest residuals in farmland, however, may be comparable to rock cover in increasing TFVs. Future experiments are required to verify the application of above equations to those systems. In addition, TFVs on crusted and undisturbed soils were not studied because of the limitation of the wind tunnel itself.

We anticipate that this method will work for crusted soils, but this needs to be tested using a field wind tunnel that can actually exceed TFVs for such soils.

4. Conclusions

[13] A physically-based, fast, and easy-to-apply method was tested to estimate soil threshold friction velocities in the field. This method relies mostly on the measurement of soil surface's resistance to disturbance instead of conventional soil texture or surface roughness. Experimental results show that the combination of air gun and penetrometer measurements provided satisfactory estimate of threshold friction velocities for sandy soils free of or with slight biological or physical crusts. For areas protected by non-erodible elements such as rocks, the air gun and penetrometer method is still promising in estimating threshold friction velocities, with a correction for rock cover. We anticipate that the method presented in this study may be also applied to estimate threshold friction velocities with the presence of other non-erodible elements, such as soil crusts and plant residuals found in other wind erosion prone systems.

References

Bagnold, R. A. (1941), *The Physics of Blown Sands and Desert Dunes*, Methuen, New York.

Batt, R. G., and S. A. Peabody II (1999), Threshold friction velocities for large pebble gravel beds, *J. Geophys. Res.*, *104*, 24,273–24,279, doi:10.1029/1999JD900484.

Belnap, J., and D. A. Gillette (1997), Disturbance of biological soil crusts: Impacts on potential wind erodibility of sandy desert soils in southeastern Utah, *Land Degrad. Dev.*, *8*, 355–362, doi:10.1002/(SICI)1099-145X (199712)8:4<355::AID-LDR266>3.0.CO;2-H.

Belnap, J., S. L. Phillips, J. E. Herrick, and J. R. Johansen (2007), Wind erodibility of soils at Fort Irwin, California (Mojave Desert), USA, before and after trampling disturbance: Implications for land management, *Earth Surf. Processes Landforms*, *32*, 75–84, doi:10.1002/esp.1372.

Cornelis, W. M., D. Gabriels, and R. Hartmann (2004), A parameterisation for the threshold shear velocity to initiate deflation of dry and wet sediment, *Geomorphology*, *59*, 43–51, doi:10.1016/j.geomorph.2003.09.004.

Dong, Z., X. Liu, and X. Wang (2002), Wind initiation thresholds of the moistened sands, *Geophys. Res. Lett.*, *29*(12), 1585, doi:10.1029/2001GL013128.

Marticorena, B., and G. Bergametti (1995), Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme, *J. Geophys. Res.*, *100*, 16,415–16,430, doi:10.1029/95JD00690.

Marticorena, B., G. Bergametti, D. Gillette, and J. Belnap (1997), Factors controlling threshold friction velocity in semiarid and arid areas of the Unite States, *J. Geophys. Res.*, *102*, 23,277–23,287, doi:10.1029/97JD01303.

Okin, G. S. (2008), A new model of wind erosion in the presence of vegetation, *J. Geophys. Res.*, *113*, F02S10, doi:10.1029/2007JF000758.

Owen, R. R. (1964), Saltation of uniform grains in air, *J. Fluid Mech.*, *20*, 225–242, doi:10.1017/S0022112064001173.

Raupach, M. R., D. A. Gillette, and J. F. Leys (1993), The effect of roughness elements on wind erosion threshold, *J. Geophys. Res.*, *98*, 3023–3029, doi:10.1029/92JD01922.

Ravi, S., and P. D'Odorico (2005), A field-scale analysis of the dependence of wind erosion threshold velocity on air humidity, *Geophys. Res. Lett.*, *32*, L21404, doi:10.1029/2005GL023675.

Ravi, S., P. D'Odorico, T. M. Over, and T. M. Zobeck (2004), On the effect of air humidity on soil susceptibility to wind erosion: The case of air-dry soils, *Geophys. Res. Lett.*, *31*, L09501, doi:10.1029/2004GL019485.

Shao, Y., and H. Lu (2000), A simple expression for wind erosion threshold friction velocity, *J. Geophys. Res.*, *105*, 22,437–22,443, doi:10.1029/2000JD900304.

Shao, Y., M. R. Raupach, and P. A. Findlater (1993), The effects of salation bombardment on the entrainment of dust by wind, *J. Geophys. Res.*, *98*, 12,719–12,726, doi:10.1029/93JD00396.

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