Enhancement of wind erosion by fire-induced water repellency

Sujith Ravi,1 Paolo D’Odorico,1 Bruce Herbert,2 Ted Zobeck,3 and Thomas M. Over4

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[1] The occurrence of fire and the subsequent increase in wind erosion are known to affect vegetation dynamics in dryland landscapes. Fires act as a disturbance on shrubs and trees and expose the soil surface to the erosive action of wind, thereby affecting the loss and redistribution of soil nutrients. Despite the relevance of wind erosion and fires to the dynamics of arid ecosystems, the interactions between these two processes remain poorly understood. We have investigated how a representative water repellent organic compound released by burning biomass and absorbed in the soil may enhance soil erodibility. To this end, we carried out a series of wind tunnel experiments, laboratory tests, and theoretical analyses to assess the effect of fire-induced water repellency on the soil susceptibility to wind erosion. The experiments were carried out using clean, well-sorted sand which was artificially coated with palmitic acid, a common water repellency inducing fatty acid found in most plants. The results indicate that fire-induced water repellency enhances soil erodibility, causing a drop in wind erosion threshold velocity. The results are explained by the effect of water repellent compounds on soil-water contact angle and on the strength of interparticle wet-bonding forces.


1. Introduction

[2] The occurrence of fire and the subsequent increase in wind erosion are known to affect the composition and structure of vegetation in dryland landscapes. Fires contribute to determine the dominance or codominance of woody plants (trees and shrubs) and grasses in arid and semiarid ecosystems [e.g., Scholes and Archer, 1997; Higgins et al., 2000; Van Langevelde et al., 2003; Sankaran et al., 2004]. Vegetation, in turn, affects the fire regime, in that both fire intensity and frequency depend on the relative abundance of trees and grasses [e.g., Andries et al., 2002; Van Wilgen et al., 2003]. Fire suppression and overgrazing have been conjectured to be able to trigger a sequence of processes, known as “bush encroachment,” leading to the conversion of desert grasslands into shrublands [e.g., Archer et al., 1988; Archer, 1989; Van Auken, 2000]. Bush encroachment is often associated with the formation of vegetation patterns characterized by patches of woody vegetation separated by bare ground. The emergence of this two-phase landscape [e.g., Schlesinger et al., 1990] may result from the positive feedback inherent to the removal of nutrient-rich soil from the intercanopy areas, to its deposition onto vegetated patches, and to the consequent formation of “islands of fertility” [Schlesinger et al., 1990]. Wind erosion is often invoked as a major factor causing soil removal from intercanopy areas and deposition in shrub patches [Okin and Gillette, 2001]. Thus, by exposing the soil surface to the erosive action of winds [Zobeck et al., 1989; Okin and Gillette, 2001], disturbances, such as fires, grazing, and climate fluctuations, act as initiators of grassland-to-shrubland conversions, while wind erosion maintains and enhances these local heterogeneities in nutrient and vegetation distribution [Schlesinger et al., 1990; Schlesinger and Gramenopoulos, 1996].

[3] Despite the relevance of wind erosion and fires to the dynamics of arid and semiarid ecosystems, the interactions between these two processes remain poorly understood. Recent experimental evidence [Whicker et al., 2002] suggests that fires enhance soil susceptibility to wind erosion: the erodibility of burned and adjacent bare unburned soil plots was found to be significantly different in the desert shrublands of the American Southwest. The burned sites were observed to exhibit lower threshold velocities for wind erosion and higher volumes of soil loss. This finding remains partly unexplained, in that it is unclear why adjacent sites, with similar surface roughness and exposure to winds, should have differing susceptibility to wind erosion. Here we show that, by affecting the strength of interparticle wet-bonding forces, fire-induced water repellency enhances soil erodibility, causing a drop in wind erosion threshold velocity (the minimum velocity for erosion to occur). Thus the mechanisms causing the enhancement of postfire soil erodibility are associated with postfire soil hydrophobicity.

[4] Fires are known for having a major impact on infiltration, runoff and water erosion [e.g., DeBano, 2000]. The postfire increase in runoff and soil erosion is caused by the decrease in infiltration capacity resulting from fire-induced water repellency [Krammes and DeBano, 1965; DeBano, 1966]. Organic compounds of chaparral and other
vegetation types are volatilized by the fire and transported into the soil by the strong temperature gradients existing through the soil profile. The condensation of these vapors develops a hydrophobic coating of fatty acids around the soil particles [e.g., DeBano, 2000]. This effect depends on the fire regime, in particular on fire temperature [e.g., DeBano, 2000; Doerr et al., 2000]. The fatty acids affect the physical-chemical properties of the grain surfaces: in particular, they increase the contact angle formed by the air-water interface with the soil grains. When this angle exceeds 90°, the capillary pressure becomes positive [e.g., Letey, 2001] preventing the adsorption of moisture onto the soil grains. Further, in the case of porous materials like soil grains some other effects exist which are associated with the roughness of the soil surface and the existence of air-filled pore spaces and air-water interfaces beneath water droplets reaching the soil surface (e.g., rainfall). These effects result in enhanced repellency of the soil, referred to as super repellency [McHale et al., 2005] and further limit the infiltration of rainfall or dew.

[i] While the effect of postfire water repellency on runoff and water erosion is relatively well understood [e.g., Doerr et al., 2000] its impact on wind erosion has never been assessed before. This is quite surprising, in that soil stabilization treatments with polysaccharides have been extensively studied in the recent past [e.g., Saleh and Letey, 1989; Ben-Hur and Letey, 1989; El-Morsy et al., 1991], while the enhancement of erodibility due to the release fatty acids from burning biomass has remained unexplored. In this paper we test through a number of wind tunnel experiments the hypothesis that fire-induced water repellency indeed increases soil susceptibility to wind erosion.

2. Materials and Methods

2.1. Soil Type and Treatments

[6] Three treatments of clean, well-sorted sand from the Ottawa, Illinois, facility of US Silica (ASTM 20/30 Unground Silica) were used for this study. Ottawa sand is used in many experimental situations because its grains are uniform in size and with small surface area (0.007 m²/g [e.g., Lee, 1999]), are spherically shaped and hence they can be modeled as uniformly sized spheres. This sand has 97% of grain sizes between 0.85 and 0.60 mm. Further, the water repellency formed as a result of fires is known to be more severe in coarse-textured sandy soils because of their smaller specific surface area compared to fine-textured soils.

[7] The compound used for the treatment, Hexadecanoic acid (Common name: Palmitic acid), is a common fatty acid found in most plants. Palmitic acid (CH\(_{17}\) (CH\(_2\))\(_{14}\)) is also able to cause water repellency in soils after heating by fire [Letey et al., 1975; Ma'shum et al., 1988; Morley et al., 2005]. Different concentrations of Hexadecanoic acid (HAD) were applied to sands to represent varying intensities of soil heating. To identify the appropriate treatments for this study, small samples (20 g) were initially treated with different concentrations of HAD. Concentrations of 0.01% and 0.1% of HAD were found to be adequate for our purposes, as treatments with higher concentrations (i.e., >0.1%) were causing the presence of clods and aggregates preventing the sand from being uniformly treated and well mixed. Further, at higher concentrations (i.e., >1%) fatty acids were observed to coat the walls of the container used for treating the soil samples. Three concentrations of HAD were thus selected: 0.1% HAD (treatment 1), 0.01% HAD (treatment 2), and the control (i.e., untreated Ottawa sand). In each treatment, 45 kg of Ottawa sand was used.

[i] The treated soils were prepared as follows: 2000 g of Ottawa sand was placed in a heat resistant plastic container (0.25 m diameter, 0.1 m height) and heated for 10–15 min in a high-power microwave. Powdered HAD (96%) was added to the sand (2 g of fatty acid in 2000 g of sand for the 0.1% treatment and 0.2 g in 2000 g of sand for the 0.01% treatment), the container was closed and the contents were mixed thoroughly by shaking the container. The heating process was continued with mixing in between (by shaking the closed container) every 3–4 min. The heating and mixing process were continued until the compound melted completely and mixed uniformly with the sand without forming aggregates. The sample was removed from the microwave and the mixing was continued until the sample reached room temperature. The same procedure was repeated several times until 45 kg were treated. The treated sands were stored (at ambient laboratory conditions) in a container and the contents were mixed thoroughly to ensure a uniform lot.

2.2. Contact Angle and Hydrophobicity Measurements

[9] The HAD (96%) crystals were melted in a small beaker. The end of a thin glass slide was dipped into this melted compound to obtain a uniform coating on the slide surface. The slide was taken out and the thin film coating of the melted compound was allowed to crystallize. Using this slide the contact angle between water droplets and the fatty acid coating was measured using a contact angle measuring instrument (Cahn Dynamic Contact Angle Analyzer DCA-315). The average contact angle was found to be approximately equal to 90° (average 89.4° and standard deviation of 0.27) which indicates a water repellent surface.

[10] The water drop penetration method was adopted to quantify the water repellency produced in the treated sands. The samples of each treatment were taken in a plastic cup (5 cm diameter and 5 cm deep). Using a pipette a drop of water was placed carefully on the surface of the soil. The time required for the drop to penetrate the surface was noted down. The water drop penetration time (WDPT) for a sample was taken as the mean WDPT for 10 droplets.

2.3. Wind Tunnel Tests

[i] The nonrecirculating wind tunnel (Figure 1) used for this study (U.S. Department of Agriculture–Agriculture Research Stations (USDA-ARS) Wind Erosion and Water Conservation Research Unit in Lubbock, Texas) is 10.0 m long, 0.5 m wide; and 1.0 m high; the test section has Plexiglas windows and is equipped with removable metal trays (1.5 cm x 46.0 cm x 100.0 cm). A fan at the end of the tunnel, powered by an electrical motor, generates the air stream by drawing air through the working section of the tunnel [e.g., Orozco, 2000]. The wind velocity was measured using a SCANIVALVE pressure transducer connected with a Pitot tube installed upwind from the soil tray at a height of 60 cm above the bottom surface of the tunnel. The bottom of the tunnel was covered with a sand paper lining with the same roughness as the soil surface in the tray. The
wind profile was measured using six Pitot tubes at different heights in the tunnel connected to different ports of the SCANIVALVE pressure transducer. These velocity values were used to calculate the parameters of the wind profile (roughness height = 0.0012 m, calculated by fitting the Prandtl-von Karman logarithmic law to the wind profile data) and to express the wind speed in terms of shear velocity ($u_*$). Saltation was measured using a SENSIT impact sensor [e.g., Stout and Zobeck, 1997] mounted in the wind tunnel with the sensitive part at a height of 2 cm from the surface and 45 cm downwind from the soil tray. Air temperature and relative humidity were recorded by a probe (Vaisala, Inc. Humititer 50 U) placed 2 mm above the soil surface and did not significantly change in the course of single experiments. Soil temperature was measured using an infrared thermometer (Exergen Corp. IRT/C.2 with Type K Germanium lens) mounted 90 cm above the soil surface. A handheld relative humidity/temperature probe (Testo, Inc. Model 610) was also used to determine ambient room temperature and relative humidity. The climatic parameters like atmospheric humidity and temperature were not controlled for these wind tunnel experiments. The air in Lubbock is generally dry and the stronger variability is due to the diurnal cycle more than to seasonal fluctuations. In order to cover a fairly broad range of relative humidity, the experiments were repeated on different days with different ambient conditions. [12] Three treatments of Ottawa sand (US Silica) were used for this wind tunnel study: 0.1% and 0.01% treatment with HAD and the no-HAD control. Each wind tunnel test consisted of three replicates of each treatment. The sands where kept on trays and allowed to equilibrate with the ambient atmospheric humidity for 8–12 hours before each wind tunnel test. The sands were not artificially wetted or dried and the wind tunnel tests were done at a range of atmospheric humidities (10–90%). Hence for all these experiments, the only source of surface soil moisture was from the atmospheric humidity. Before each wind tunnel test the Pitot tube and its transducer were calibrated and corrections were made for changes in atmospheric temperature. The trays were then placed in the wind tunnel and the motor was activated. The air flow was initially increased stepwise to attain a wind speed just below the threshold value and then increased slowly until the particle impact sensor indicated particle movement. The threshold velocity was determined as the velocity at which an abrupt increase from zero to more than 100 particle impacts per second was observed. Statistical analysis (ANOVA) were done to show that the threshold velocity values were significantly different for the control and the treated soils. 2.4. Estimating the Moisture Content of the Water Repellent Soils [13] The water repellency in the treatments was induced by mixing the Ottawa sand with HAD at the required concentrations as described in section 2.1. Soil from the top 2 mm was sampled from the controls and the treated soil trays after the each wind tunnel test, and the soil moisture from each sample was measured gravimetrically. In our previous studies done under same range of ambient conditions (10–90% RH) it was shown that the wind tunnel experiments were not affected by soil drying during the tests [Ravi et al., 2004, 2006]. The melting point of HAD is approximately 63°C; thus the standard procedure to calculate gravimetric soil moisture by oven drying cannot be followed because a considerable amount of organics would be lost along with the soil moisture in the course of the drying process. To account for this loss of organics during oven drying and to accurately measure the moisture content of these treated soils, the palmitic acid concentrations (from total carbon content) of each treatment and of the control.
were measured before and after oven-drying using a CN analyzer (Carlo Erba Elemental Analyzer NA1500). The soil treated with 0.01% concentration of organics was found to be extremely heterogeneous, i.e., with a nonuniform coating of the sand grains with HAD. Hence the carbon and moisture content (not shown) were found to be extremely heterogeneous in the 0.01% treated sand. Statistical analysis (ANOVA) were done to test the significance of the variations in surface soil moisture between the control and the treated soils for the four classes of relative humidity considered in this the study.

2.5. Water Retention Curves

[14] The moisture retention curves (Figure 2) for the control and treatments were determined by measuring the water potential values (using a water activity meter, DECAGON AquaLab Series 3T) and moisture content (gravimetrically, with adjustment to account for the loss of organics during oven drying). The water activity meter used in this study can determine soil matric potentials above −300 MPa with an accuracy of ±0.003 water activity units [Gee et al., 1992]. Water activity readings, $a_w$, were converted into matric potential values as $\psi_m = RT/M \ln (a_w)$, where $\psi_m$ is the matric potential, $R$ is the gas constant, $M$ is the molecular mass of water, and $T$ is the Kelvin temperature.

3. Results

3.1. Water Drop Penetration Time

[15] The repellent soils made in the laboratory were tested for the extent of water repellency induced by the organic coatings using the water drop penetration method. This analysis showed that the organic coatings on the soil grains were able to induce water repellency in both the HAD treated sands. The control sand was perfectly wettable, with water drops penetrating the soil surface instantly. The repellent soil treatments were not easily wettable: the water drop penetration time (WDPT) for the samples treated with 0.01% of palmitic acid ranged between 5 and 6 hours, while for soil treated with 0.1% of the same compound the WDPT was 8–9 hours. These results indicate that the organic coating did induce water repellency and that this hydrophobicity was stronger in soils treated with higher concentrations of HAD.

3.2. Wind Tunnel Experiments

[16] The effect of water-repellent coatings on wind erosion threshold velocity was assessed under different levels of atmospheric humidity through wind tunnel tests carried out on three soil treatments. The primary experimental result of this study is that in each of the four different humidity ranges considered (i.e., 10–30%, 30–50%, 50–70%, and 70–90%) the threshold velocity was highest for the control sand (Figure 3) and decreased with increasing concentrations of fatty acid. The differences between the threshold velocity values of control and 0.01% treated sand and between 0.01% and 0.1% treated sand were found to be significant (p < 0.0001) in all the humidity classes, while the surface moisture content of the control and 0.1% treated sands were found to be not significantly different for all the humidity classes (p > 0.05). Thus the statistical analyses show that the threshold velocity values were significantly different for the control and the treated soils even though the surface moisture contents were not significantly different. Moreover, for each treatment the threshold values increased with increasing air humidity, indicating the existence of a clear dependence of threshold velocity on air humidity (Figure 3). In this case, due to the absence of clay fractions the effect of absorbed moisture on interparticle bonding was different from our previous findings [Ravi et al., 2004, 2006; Ravi and D’Odorico, 2005] in that the threshold velocity for wind erosion exhibited a monotonic increase with the humidity of overlying air.

3.3. Surface Soil Moisture and Water Retention Curves

[17] Surface soil moisture of the control was observed to increase with increasing near-surface air humidity (Figure 4) consistently with our previous studies [Ravi et al., 2004, 2006]. These results indicate that in the absence of other
inputs of water, surface soil moisture (hence the threshold velocity) was controlled by near-surface atmospheric humidity. The sensitivity of surface water content on relative humidity was found to be stronger for the control soil than for the treatment #1 (0.1% of HAD). However, the surface moisture content of the treatment with 0.1% concentration of the HAD was also found to increase with increase in air humidity. The moisture content of the treatment was consistently (slightly) higher than the control for the different humidity ranges considered for this study, though for some of them the differences in moisture content between treated and untreated soils were found not to be significantly different (Figure 4). The water retention curves (Figure 2) were almost similar for the control and the treated soil (0.1%) which indicated that these soils did not differ significantly in moisture retention properties.

4. A Theoretical Framework for the Modeling of Liquid-Bridge Bonding

Theories for the estimation of the threshold velocity for wind erosion generally do not account for the dependence on the contact angle, $\gamma$, which is usually taken equal to zero [Fisher, 1926; McKenna-Neuman and Nickling, 1989; Cornelis et al., 2004]. This angle expresses the effect of the physical-chemical properties of soil grains and liquid (i.e., water) on the interaction between the grain surfaces and the fluid (Figure 5), while the surface tension is a
property of the fluid only. The organic coating changes the contact angle in the treated soils thereby affecting the interparticle force due to liquid bridges between the adjacent soil particles. We adopt the theoretical framework developed by Fisher [1926] to show the impact of contact angle on interparticle forces \( F_i \) associated with liquid-bridge bonding between spherical particles. Liquid bridge bonding consists of capillary forces associated with (1) the tension due to the curvature of the air water interface and (2) the pressure deficit between the pore air and the water in the liquid bridge [e.g., Cornelis et al., 2004]. In the case of spherical soil grains [Fisher, 1926] the interparticle force is

\[
F_i = 2\pi b T \cos \psi + \pi b^2 T \left( \frac{1}{c} - \frac{1}{b} \right)
\]  

where \( T \) is the surface tension of water, \( b \) is the radius if the fluid neck connecting two spherical grains, \( c \) is the radius of the meridian curve and \( (1/c - 1/b) \) represents the total curvature of the surface at this point (see Figure 5).

In nonrepellent soils the contact angle is \( \gamma = 0^\circ \), while the maximum hydrophobicity is attained when \( \gamma = 90^\circ \). We generalize Fisher's theory to account also for the dependence on the contact angle. From simple geometric considerations (Figure 5) we have that \( \psi = \pi/2 - (\theta + \gamma) \) and

\[
c = r \frac{(1 - \cos \theta)}{\cos(\theta + \gamma)}, \quad b = r \sin \theta - c \left[ 1 - \cos \left( \frac{\pi}{2} - (\theta + \gamma) \right) \right]
\]  

Expressing the interparticle force given by equation (1) in terms of contact angle \( \gamma \), \( F_i \) becomes

\[
F_i = 2\pi b T \sin(\theta + \gamma) + \pi b^2 T \left( \frac{1}{c} - \frac{1}{b} \right)
\]

with \( b \) and \( c \) depending on \( \gamma \) (equation (3)).

The value of \( \theta \) was given by Fisher [1926] as a function of the moisture content for open packing and closed packing systems. In our case we found that the moisture content (hence the angle \( \theta \)) remained about the same between treated sands and the control. In the numerical calculations shown in Figure 6 we use a value of relative soil moisture, \( s = 12.5\% \) (expressed as percentage of pore space). The corresponding values of \( \theta \) are \( 40^\circ \) and \( 25^\circ \) for the open and close packing, respectively [Fisher, 1926, Table 1]. Equation (3) can be rewritten in dimensionless form as

\[
\frac{F_i}{\pi r T} = \left( \frac{b - c}{c} + 2 \sin(\theta + \gamma) \right) \frac{b}{r}
\]

where the right-hand side is a function only of the moisture content (through the angle \( \theta \)) and of the contact angle, \( \gamma \). Figure 6 shows a plot of \( F_i/\pi r T \) calculated using equation (4) as a function of the contact angle \( \gamma \) for the cases of close and open packing.

5. Discussion

The existence of higher moisture contents in water repellent soil seems to be counterintuitive, as water repellent soils are expected to adsorb less moisture from the overlying atmosphere. However, these results confirm the findings by Barrett and Slaymaker [1989], who observed that water repellent soils can absorb water. These authors suggested that water can move more freely as vapor in a water repellent soil than in a normal soil, allowing soil water to be redistributed even though the adsorption capacity of water repellent soil grain surfaces for water molecules is small. Vermeire et al. [2005] observed, in field plot experiments, that the repellent soils had about the same moisture contents compared to control soils. Doerr et al. [2000] reviewed three different mechanisms that can be invoked to explain this counterintuitive behavior. In summary, a conclusive theory for water absorption by hydrophobic soils is still missing.

The results from the wind tunnel tests indicated that the water repellent sands were more susceptible to wind erosion compared to the control sand. The statistical analyses show that the threshold velocity values were signifi-

Figure 5. (a) Liquid bridge between two uniform spherical soil grains. (b) Contact angle (\( \gamma \)) between two uniform spherical soil grains with radius \( r \). From simple geometric consideration we have that \( \psi = \alpha = (\pi/2) - (\theta + \gamma) \).
cantly different for the control and the treated soils even though the surface moisture contents were not significantly different.

Three possible mechanisms may (in general) explain the decrease in threshold velocities for water repellent soils: (1) the effect of hydrophobicity on moisture adsorption on treated soils; (2) the geometry of the adsorbed layers, and (3) the effect of water repellent coatings on the contact angle. In the following discussion we will show to what extent these mechanisms can be invoked to explain the effect of water repellency on soil erodibility.

[23] The condensation of water in the form of droplets adsorbed onto surfaces of water repellent grains is, in general, limited in hydrophobic soils [Osmet, 1963] (see also Figure 7). At lower humidities (before the formation of liquid bridges) moisture content could affect the threshold velocity through an “added gravity effect” (i.e., these soils might be expected to retain less adsorbed water and to be consequently lighter and with a lower threshold velocity.

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**Figure 6.** Dependence between inter particle force and contact angle, \( \gamma \) (equation (2)) for a close packing (circles) and open packing (diamonds) systems with 12.5% moisture content (expressed as percent of pore space, i.e., \( s = 0.125 \)). The angle \( \theta \) (Figure 5) depends both on moisture content and on soil packing.

**Figure 7.** Photos taken with environmental scanning electron microscope of treated and untreated soil grains (at RH 80–90%). There is a clear difference in moisture adsorption onto grain surfaces for the control and repellent soil. The control soil has grains with a uniform coating of adsorbed water, while moisture is adsorbed onto the 0.1% treated soil with an irregular distribution of water droplets condensing on grain surfaces (indicated by the arrow).
[e.g., Gregory and Darwish, 1990]). However, in our case, the fact that both the moisture content and the water retention curves (Figure 2) were about the same for the control and the treated soil (0.1%) suggests that these soils did not differ significantly in moisture retention properties. Thus the lower threshold values observed for water repellent soils in our study cannot be attributed to weaker moisture adsorption on the grain surface than in the control. However, the more irregular geometry of the adsorbed layers formed on HAD-treated soil grains (Figure 7) might have affected the strength of the adsorbed-layer forces by reducing the contact area between adjacent adsorbed layers. This reduction would be similar to the effect of surface roughness on the soil grains investigated by Harnby [1992].

[25] As the atmospheric humidity increases, the thickness of the adsorption film increases and eventually reaches a stage when condensation starts to occur in the contact points between the particles, thereby forming a liquid bridge [Harnby, 1992]. The repellent coatings on the soils can delay the formation of liquid bridges, or even prevent their formation in cases of extremely water repellent soils. In such cases, i.e., when the contact angle exceeds 90°, the capillary pressure becomes positive [e.g., Letey, 2001] preventing penetration of moisture in the interstices between soil particles. This limitation on moisture penetration significantly reduces the interparticle forces associated with moisture bonding. Two different mechanisms contribute to wet-bonding forces in soils [e.g., Ravi et al., 2006], namely, adsorbed-layer bonding in relatively dry soils, and liquid-bridge bonding in wetter soils. In our previous work we have indicated RH ≈ 60% as a reference threshold value for the formation of liquid bridges. We have also shown that for RH < 60%, i.e., when the effects of adsorbed-layer bonding are stronger, the threshold velocity decreases with increasing values of RH (hence with increasing moisture contents [Ravi et al., 2004, 2006]). This effect was not observed in the soils used in this study (not even in the control), probably due to the low adsorptive capacity of these sandy soils, with no clay fractions. Thus we argue that adsorbed-layer bonding was weak both in the control and in the treated soils. The dependence of threshold velocity on moisture content (i.e., on RH) was probably due to capillarity and to early stages of liquid bridge formation even in air dry soils (i.e., RH < 60%). Since the moisture absorption explanation does not appear to work (except for the likely effect of the treatment on the geometry of the adsorbed layer), due to the low adsorptive capacity of these soils and the insignificant differences in moisture content between treated soils and the control, let us explain the difference in soil erodibility for the three treatments as the effect of changes in the contact angle between liquid bridges and the soil grains. Liquid bridge-bonding is known for being the dominant interparticle bonding force [Cornelis et al., 2004] in relatively wet soils (e.g., RH > 60%) and we argue that at the early stages of bridge formation it may limit the erodibility also of air-dry, clay-free sandy soils. Figure 6 shows the effect of the contact angle on interparticle forces due to liquid-bridge bonding. It is observed that a maximum can be observed, beyond which the treatment force increases with contact angle. The F/Tπ values overall decrease when the contact angle increase from 0° (perfectly wettable soil) to 90° (perfectly water repellent soil). This result indicates that the interparticle forces associated with wet-bonding effects decrease with increasing degrees of water repellency. The interparticle bonding force (F) is related to threshold velocity (u*) for wind erosion as [e.g., McKenna Neuman, 2003; Cornelis et al., 2004]

$$u_* \propto \sqrt[3]{1 + \frac{F/B}{8(\rho_s - \rho_a)g\rho}}$$

where \( \rho_s, \rho_a \) are the densities of the soil grains and air, respectively, g is the acceleration due to gravity, and B is a constant (electrostatic forces between the soil grains are not considered in this expression as these forces are negligible for sandy soils). Thus the decrease in interparticle forces explains the consistent decrease in threshold velocity that we found (Figure 3) with increasing concentrations of soil organic repellents (i.e., increasing values of \( \gamma \)) despite the moisture contents and water retention characteristics were comparable.

[26] The effect of enhancement of soil erodibility by fires depends also on a number of factors that have not been addressed in this study. For example, the level of soil hydrophobicity developed by fires depends on fire intensity, vegetation cover, and soil texture. Other authors have already investigated how these factors affect the formation of water repellency on the soil surface [e.g., Doerr et al., 2000]. Our research focused directly on the effect of water repellency on soil erodibility. Thus the results can be applied also to the case of water repellency produced by vegetation in the absence of fires. This nonpyrogenic repellency can be by itself significant, especially in coarse textured soils [e.g., Bond, 1964]. Further, this study focused only on postfire enhancement of mineral soil erodibility, while other effects associated with the deflation of surface ashes and other light combustion products have not been investigated. This loose, nutrient-rich organic material is readily lost from the burned site by wind erosion. The effect of soil water repellency on wind erosion is expected to come into play once most of the light, charred and burned surface material has been removed.

6. Conclusions

[27] Our results experimentally support the hypothesis that fire induced water repellency in arid soils significantly affect the soil susceptibility to wind erosion. This study has shown that the 0.01% and 0.1% treatments with HAD were able to induce significant water repellency in soils. These repellent soils showed neither a significant change in moisture retention curves or in the moisture content. However, water repellency was able to induce important changes in the threshold shear velocity for wind erosion, which was found to decrease with the increasing degrees of soil water repellency. The results were explained as an effect of the increase in soil-water contact angle (induced by the organic coating of the soil grains) on the strength of interparticle wet-bonding forces. Through a theoretical framework developed to express the wet bonding forces as a function of contact angle it was shown that water repellency weakens the interparticle forces, thereby enhancing soil erodibility by wind.
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B. Herbert, Department of Geology and Geophysics, Texas A&M University, College Station, TX 77843-3115, USA. (herbert@geo.tamu.edu)

P. D’Odorico and S. Ravi, Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903-4123, USA. (paolo@virginia.edu; sujith@virginia.edu)

T. M. Over, Department of Geology and Geography, Eastern Illinois University, Charleston, IL 61920, USA. (tmover@eiu.edu)

T. M. Zobeck, Wind Erosion and Water Conservation Research Unit, USDA, Agricultural Research Service, Lubbock, TX 79415, USA. (zobeck@lb.ars.usda.gov)