Dust supply varies with sagebrush microsites and time since burning in experimental erosion events

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[1] Wind erosion and large dust plumes are an increasingly important attribute in cold-desert rangelands, particularly as wildfire increases. Fire reduces vegetation, which increases erosivity. Whether sediment supply increases after fire has not been determined in this environment. We asked how sediment supply varied among sites burned 2-months to 5-years previously, in comparison to unburned sagebrush steppe, across 500 km of southern Idaho, USA. We measured potential dust emissions (PM10, particles <10 μm diameter) in response to step changes in friction velocity ($u_*$), with a field-based wind tunnel analog (PI-SWERL, Portable In Situ Wind Erosion Laboratory). We evaluated how emissions, sediment supply, and a proxy of erodibility varied among the microsite soil patterning in these sites (shrub islands and interspaces). Emissions were three orders of magnitude greater on burned compared to unburned surfaces, especially where shrubs had existed and sites burned more recently. Greater emission rates were due to greater sediment supply, whereas the proxy of erodibility did not vary among the surfaces for dry conditions that prevail during large wind erosion events (near −150 MPa at the surface). Wetter surface conditions, similar to those after precipitation or snowmelt, resulted in less dust emission on a recently burned site. Dust supply increases in initial postfire years especially on microsites that previously had shrubs. Abundance of shrubs is responsive to management practices that affect prefire vegetation, and grazing-induced increases in shrubs might, for example, render a site more vulnerable to dust emissions following fire.


1. Introduction

[2] Dust emission is an increasingly cited environmental issue from shrub deserts, and a better understanding of sources and controls is needed [Neff et al., 2008; Field et al., 2009a]. Dust emission is most directly affected by erosivity (i.e., the ability of the wind to entrain particles), erodibility of the soil (i.e., the soil’s susceptibility to entrainment), and supply of erodible sediment [Okin et al., 2006]. Fire is one of the most prevalent mechanisms that can affect erosivity in desert shrub- and grassland, specifically through the reduction of the aerodynamic boundary layer attributed to plants and concomitant increase in connectivity of bare soil [Okin et al., 2009]. Fire may also increase erodibility through heating-induced biochemical alteration of the soil surface [Ravi et al., 2007], and erodibility can vary with fluctuations in soil and atmospheric moisture following fire [Sankey et al., 2009b]. Erodibility has been measured in the field for recently burned shrub deserts [Sankey et al., 2009a, 2009b], though not at fine spatial scales of individual shrub and shrub-interspace microsites. Less is known about the inherent erodibility of unburned shrub deserts, particularly where undisturbed vegetation is sufficient to limit or eliminate erosion and dust emissions such that erodibility cannot be determined without experimentally manipulating wind. Under stable vegetation cover and moisture near the soil surface, the abundance of erodible sediment likely limits the magnitude and duration of dust events, yet few studies have attempted to characterize supply of erodible sediment in the context of fire and microsites.

[3] Feedbacks between surficial processes and vegetation patterns in shrub deserts can profoundly affect biogeochemical and geomorphic patterns, from coarse geographic scales to fine spatial scales of individual plants and interspaces between plants [Breshears et al., 2009; Field et al., 2009b; Okin et al., 2009; Ravi et al., 2010a, 2010b; Sankey et al., 2011]. In these environments, shrub islands of fertility develop due to greater biologic activity and improved soil hydrology under shrubs [Schlesinger et al., 1996]. Aeolian processes that scour interspace microsites and redistribute
A central theme was the question of whether shrublands and shrub-encroached grasslands of warm desert environments differ from mechanisms and feedbacks proposed for warm desert versus those of cold deserts. In particular, shrub and total vegetation cover are generally greater for cold compared to warm desert, and bare (interspace) soil surfaces have been demonstrated to be less prevalent and smaller in size for cooler and wetter cold deserts [de Soyza et al., 2000]. We expected that our study might elucidate the degree to which fine-scale interactions of geomorphic and ecologic processes in cold desert shrublands do or do not differ from mechanisms and feedbacks proposed for warm desert of the USA.

The specific research question of our study was: do potential dust emissions and sediment supply differ for burned versus unburned sagebrush steppe, in undershrub versus interspace microsites, on naturally dry soils across the Snake River Plain of Idaho – a cold desert shrubland? We hypothesized that the potential dust emissions and sediment supply would be greater for burned versus unburned sagebrush steppe, and for undershrub versus interspace microsites. We additionally considered whether variability in a proxy of erodibility derived from the PI-SWERL was evident for burning and microsite effects. We studied sites with a range of recent fire histories to examine the extent to which potential dust emissions and sediment supply varied with time since burning. We additionally examined relationships of moisture with potential dust emissions on burned surfaces that were wetted, and expected that erosion would decrease with increased moisture. We considered the implications of results on feedbacks between vegetation and surficial processes for cold desert – a central theme was the question of what is the combined ecological and geomorphic role of bare-ground (i.e., interspace) soil surfaces in cold desert?

2. Study Area

This study was conducted in sagebrush steppe of southern Idaho and the Snake River Plain (SRP) across a significant portion of the northern Great Basin and southern Columbia Plateau. The study was carried out from 18 to 24 June 2010 during an extended high pressure system with no rain. We performed experiments at 5 sites that comprised burned and nearby, biogeomorphically similar unburned locations at five different wildland fires that spanned a very large proportion of the entire west–east expanse of the SRP (Figure 1). The five fires comprised a chronosequence of recent fire histories and ordered chronologically are: Clover (burned July 2005, 1200 m above sea level), Moonshiner (August 2007, 1650 m), Noman (July 2009, 1350 m), Sand Hollow (August 2009, 900 m), Samaria (April 2010, 1450 m). All sites have snow cover for some portion of the year, and annual snowfall ranges from ~250 mm at Sand Hollow, to ~340 mm at Clover and Noman, ~660 mm at Moonshiner, and ~760 mm at Samaria. Annual mean precipitation for each site is: 260 mm (Clover), 220 mm (Moonshiner), 220 mm (Noman), 350 mm (Sand Hollow), and 370 mm (Samaria).

Plant communities were predominantly big sagebrush (Artemisia tridentata, primarily ss普通 wyomingensis, with some ss普通 vasyanensis and tridentata at Samaria) and bunchgrasses in the unburned sites, with encroaching junipers at Samaria (juniper microsites were not sampled) surrounded by patches of exotic cheatgrass (Bromus tectorum), P. spicata, Lupinus sp. and a diverse mix of other herbs. Vegetation of the burned sites ranged from an exotic mix of cheatgrass, crested wheatgrass (Agropyron cristatum), tumblemustard (Sisymbrium altissimum) and native Poa secunda at Sand Hollow; crested wheatgrass at Noman and Clover;
a diverse and rich native mix of herbs at Moonshiner (P. secunda, Elymus elymoides, P. spicata, Lappula occidentalis, Collinsia parviflora, and numerous species in the genera Phlox, Astragalus, and Erigeron [Hoover, 2010]. There was very little vegetation remaining on the Samaria fire during our sampling (just 2 months following burning) and what was present consisted of a sparse array of newly germinated exotic and invasive species such as Helianthus annus, Tragopogon dubius, Lactuca serriola, Kochia scopularum, cheatgrass, and a few natives such as Balsamorhiza sagittata.

The geomorphology of the region is dominated by the SRP, an alluvial plain that is overlain by predominantly aeolian, and to a lesser degree fluvial, sediments that are thousands to tens of thousands of years old [Busacca et al., 2004]. The alluvial plain itself resides on basalt flows and calderas that are 16 ma and younger [Pierce and Morgan, 1992]. Topography at the Clover, Moonshiner and Noman sites is lower relief terrain that is characteristic of the interior of the SRP (Figure 1). Topography at the Sand Hollow and Samaria sites is hilly and more characteristic of the bedrock-controlled margins of the SRP. The sites represent a range of classified soil types that include the Aridisols, Mollisols and Entisols soil orders [National Resources Conservation Service (NRCS), 2010]. Soils at the Clover site are classified as Xerollic and Haploxerollic Durargids and Camborthids [NRCS, 2010]. Soils at the Moonshiner site are classified as Sodic Xeric Haplocalcids [NRCS, 2010]. The Noman site is predominated by Lithic Xerollic Camborthids and Xerollic Haploargids [NRCS, 2010]. The Sand Hollow site is characterized by Aridic and Aridic Calcic Haploxerolls and Argixerolls as well as Xeric Torrifluvents [NRCS, 2010]. The Samaria site is predominated by Lithic and Typic Calcixerolls [NRCS, 2010].

3. Methods
3.1. Naturally Dry Surfaces
3.1.1. Data Collection and Processing
[10] We made measurements with the Portable In Situ Wind Erosion Laboratory (PI-SWERL) at 4 paired under-shrub and interspace microsites within each burned and unburned treatment at the chronosequence of five sites (4 microsite pairs × 2 burn treatments × 5 sites = 40 pairs and 80 total measurements). The PI-SWERL simulates wind shear at the ground surface with a rotating annular blade. A dust monitor (TSI, Dustrak Model 8520) in the PI-SWERL measures concentrations of particles <10 μm in diameter (PM10) and optical gate sensors (OGS) identify saltating particles entrained by the wind shear. At each measurement, we used the same “modified ramp test” with the PI-SWERL, which lasted a total of 500 s, during which the rotation of the annular blade was increased incrementally from 0 to 4000 RPM with 3 sustained periods of time when the blade rotated at 2000, 3000, and 4000 RPM [Dust-Quant LLC, 2008]. The RPM levels corresponded to an equivalent friction velocity (u*) imparted on the ground surface during these tests that ranged from 0 to 0.69 m s⁻¹ based on empirical measurements presented by Etvemezian et al. [2007]. The effective surface area on which the PI-SWERL operates is 0.026 m² and the diameter of the footprint of the
Table 1. Study Site Mean (Standard Error) Particle Size (n = 4), Organic Matter (n = 12), and Unburned Sagebrush Establishment Dates (n = 4)

<table>
<thead>
<tr>
<th>Site</th>
<th>PM10 (%)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>OM (%)</th>
<th>Texture Class</th>
<th>Sagebrush Establishment (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clover</td>
<td>46 (3)</td>
<td>23 (4)</td>
<td>40 (2)</td>
<td>37 (2)</td>
<td>9 (2)</td>
<td>Clay loam</td>
<td>1969 (8)</td>
</tr>
<tr>
<td>Moonshiner</td>
<td>28 (5)</td>
<td>41 (3)</td>
<td>40 (3)</td>
<td>19 (5)</td>
<td>10 (1)</td>
<td>Loam</td>
<td>1987 (4)</td>
</tr>
<tr>
<td>Noman</td>
<td>43 (4)</td>
<td>31 (2)</td>
<td>33 (3)</td>
<td>36 (4)</td>
<td>8 (1)</td>
<td>Clay loam</td>
<td>1994 (1)</td>
</tr>
<tr>
<td>Sand Hollow</td>
<td>19 (9)</td>
<td>70 (11)</td>
<td>15 (4)</td>
<td>15 (8)</td>
<td>7 (1)</td>
<td>Sandy loam</td>
<td>1998 (1)</td>
</tr>
<tr>
<td>Samaria</td>
<td>44 (7)</td>
<td>26 (6)</td>
<td>40 (1)</td>
<td>34 (6)</td>
<td>15 (1)</td>
<td>Clay loam</td>
<td>1999 (3)</td>
</tr>
</tbody>
</table>

entire cylindrical instrument when placed on the ground is approximately 0.3 m [Dust-Quant LLC, 2008]. For more in-depth reading on the PI-SWERL instrument we refer readers to Etyemezian et al. [2007].

[11] Prior to placement of the PI-SWERL at the unburned undershrub microsites we removed the sagebrush shrub to ground level with a handsaw, and later estimated the age of each removed shrub for additional site characterization information. Herbaceous vegetation was carefully clipped to the ground surface and sticks, rocks and litter large enough to damage the instrument (loose materials with diameter > ~1 cm) were removed prior to placement of the PI-SWERL. Data recorded by the PI-SWERL that we analyzed included the total mass of PM10 entrained from the surface during the 500 s test (hereafter referred to as “total mass PM10” or “total PM10”), the instant flux (µg s⁻¹) of PM10 for each second of the 500 s test (herefore “instant flux PM10”), and the rate of PM10 emitted per unit ground area (units of µg m⁻² s⁻¹ and heretofore “PM10 emission rate”), which was determined by dividing the instant flux by the surface area on which the PI-SWERL operated (0.026 m²) [Dust-Quant LLC, 2008].

[12] The OGS provide an estimate of salination that is at the same temporal resolution and strongly correlated with the PM10 concentrations estimated by the dust monitor [Dust-Quant LLC, 2008]. For three measurements (2 burned undershrubs and 1 burned interspace at the Samaria site) PM10 concentrations approached the recommended upper limit for the dust monitor and we turned off the monitor for the final portion of the measurement. In these instances we used a linear regression (all r² > 0.93) of PM10 concentrations and OGS counts to estimate the PM10 concentrations for the portion of the measurement that the monitor was turned off [Dust-Quant LLC, 2008]. Due to the strong correlation between PM10 concentrations measured with the monitor and OGS estimates of salination, we consider the variables derived from PM10 concentrations (total mass, instant flux, and emission rate) as general measures of the relative erosion potential of each microsite [Bacon et al., 2011].

3.1.2. Soil Description

[13] Soil moisture near the surface can be an important control on dust emissions, and aeolian transport generally occurs during periods of relatively low atmospheric moisture. We attempted to minimize variability in moisture among study sites for the analysis of potential dust emissions from naturally dry microsites, by conducting experiments during a relatively short and targeted period (1 week) of dry atmospheric conditions with no rain (i.e., conditions under which wind erosion generally occurs in this environment). We determined gravimetric water content for a composite of 3 subsamples from the upper 1 cm of soil within the microsite at each PI-SWERL measurement location. At the Samaria and Moonshiner sites we additionally determined: (1) soil water potential for a sealed sample of surface soil in the lab using the chilled-mirror dewpoint method (model WP4T, Decagon Devices, Pullman WA), and (2) volumetric water content in the field where we made PI-SWERL measurements with a Hydrosense® probe (Campbell Scientific Inc., Logan, UT, USA) inserted horizontally 1 cm below the surface.

[14] We characterized particle size distribution (sand, silt, clay, and PM10 fractions) for samples collected from the upper 2 cm of the soil surface from one pair of undershrub and interspace microsites in burned and unburned treatments at each site (n = 4, including 1 unburned undershrub, 1 unburned interspace, 1 burned undershrub, and 1 burned interspace per site). We characterized particle size distribution for the fraction of the samples with particle diameter <2 mm (Table 1) using the hydrometer method with peroxide pretreatment to remove organic matter [Soil Survey Staff, 2009]. We did not analyze differences in particle size by burn treatment and microsite because these effects have been found to be very small and often statistically insignificant in related work in this environment [Hoover, 2010].

[15] We characterized organic matter content (OM) for samples collected from the upper 2 cm of the soil surface from three pairs of undershrub and interspace microsites in burned and unburned treatments at each site, with the exception of the burned treatment at the Samaria site where we collected samples from 2 pairs. We characterized OM using mass loss upon combustion (440 C for 24 h) [Soil Survey Staff, 2009]. OM is expected to vary among microsites and burn treatments in this environment [Hoover, 2010]. To provide a more complete depiction of soil surface OM we present estimates of mean (SE) OM content averaged by study site, as well as averaged by burn treatment and microsite among study sites.

3.1.3. Fire, Microsite, and Site Effects

[16] A mixed model analysis was performed in SAS software (Proc MIXED) with the natural logarithm of total mass PM10 as the dependent variable, and site, burn treatment, and microsite as fixed effects with all possible interaction terms. The paired observation was the unit of analysis. When a predictor variable was statistically significant, post hoc comparisons were performed using a Tukey’s adjustment to protect the experiment-wise error. Differences were considered significant if p < 0.05.
Table 2. F-values, Significance Level (P-value), and Degrees of Freedom From Mixed Model Analysis for Response of Total Mass of PM10 Emitted From the PI-SWERL Tests to the Effects of Site, Burn Treatment (Burned, Unburned), Microsite (Undershrub, Interspace), and Interaction Terms

<table>
<thead>
<tr>
<th>Effect</th>
<th>Total Mass PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>F-value P-value</td>
</tr>
<tr>
<td>Site*Burn</td>
<td>27.36 0.000</td>
</tr>
<tr>
<td>Burn</td>
<td>210.11 0.000</td>
</tr>
<tr>
<td>Microsite</td>
<td>24.30 0.000</td>
</tr>
<tr>
<td>Burn*Microsite</td>
<td>15.71 0.000</td>
</tr>
<tr>
<td>Site*Microsite</td>
<td>3.52 0.018</td>
</tr>
<tr>
<td>Burn*Site</td>
<td>23.48 0.000</td>
</tr>
<tr>
<td>Site<em>Burn</em>Microsite</td>
<td>2.10 0.106</td>
</tr>
</tbody>
</table>

3.1.4. Sediment Supply and Erodibility

Changes in PM10 emission rates with changes in \( u_* \) and time for PI-SWERL trial runs were examined for similarities and differences in sediment supply and a proxy of erodibility among study sites, burn treatments, and microsites. Each PI-SWERL trial run consisted of three “ramp” and three “step” portions of the test (for example, the first ramp occurred 60–120 s into each test during which time \( u_* \) increased from 0.09 to 0.39 m s\(^{-1}\), the first step occurred 120–180 s into each test during which time \( u_* \) remained constant at 0.39 m s\(^{-1}\)). The equivalent friction velocity value at which a rise to a peak in mean PM10 emission rate was initiated was estimated and evaluated as a proxy for erodibility. Supply of erodible mass was evident if an increase in mean PM10 emission rate was sustained during a step (i.e., at constant \( u_* \)), and a decrease in PM10 during a step was an unambiguous indication of supply limitation for that equivalent friction velocity [Sweeney et al., 2008].

3.2. Wetted Surfaces

We performed an additional set of measurements with the PI-SWERL at the area burned by the Samaria fire in which the soil surfaces were experimentally wetted. The purpose was to examine potential dust emissions, sediment supply, and a proxy of erodibility under wetter conditions than the naturally dry conditions that were targeted during the measurements at the chronosequence of five sites. Nine burned locations on undershrub microsites were wetted with a sprayer. We applied water evenly within each location but for different length of time so that locations varied in degree of wetness. We collected samples of soil for water potential and gravimetric water content measurements from each location after wetting and prior to PI-SWERL measurements. Water potential and gravimetric water content were measured as described above for the locations at Samaria and Moonshiner that were not wetted. We performed PI-SWERL measurements for the wetted locations with the same “modified ramp test” as used for non-wetted locations. We examined plots of PM10 emission rates, instant flux, or friction velocity as a function of time during each PI-SWERL trial for evidence of supply limitation and variability in a proxy of erodibility, similarly as described for non-wetted plots. From plots of instant flux of PM10 as a function of time, we estimated the largest value of equivalent friction velocity at which a rise to a peak in instant flux of PM10 was initiated as a proxy of erodibility (henceforth referred to as \( u_{*crit-PI-SWERL} \)) during the PI-SWERL trial for each of the nine locations. We examined relationships of total mass PM10 and the largest value of instant flux from each measurement (maximum instant flux) with water potential as well as with \( u_{*crit-PI-SWERL} \) using linear regression analysis. We similarly examined the relationship of \( u_{*crit-PI-SWERL} \) and water potential.

4. Results

4.1. Naturally Dry Surfaces

4.1.1. Soil Description

The soil surfaces of the microsites were dry for all sites and burn treatments (non-wetted surfaces). Gravimetric water content of the upper 1 cm of soil ranged from 0 to 7% among all sites and the average at each site was <3%. The additional volumetric water content and soil water potential values determined near the surface for the Samaria and Moonshiner sites were <5% and <127 MPa, respectively. Surface soil texture ranged relatively broadly from Clay loam-Sandy loam, mean PM10 content of the soil surface was ~20–50% (by mass), and mean OM ranged from 7 to 15% (by mass), among study sites (Table 1). Mean (SE) OM % determined by burn treatment and microsite among study sites was 13 (2) and 6 (1) for unburned undershrubs and interspaces, and 11 (1) and 8 (1) for burned undershrubs and interspaces, respectively. Shrub ages estimated from removed stumps of sagebrush in unburned treatments ranged from 8 to 52 years with mean establishment date of 1990 (standard deviation = 13 years) among all sites (Table 1).

4.1.2. Fire, Microsites, and Time

The mass of PM10 emitted was up to three orders of magnitude greater on burned surfaces compared to unburned surfaces, particularly on microsites that previously had shrubs (Table 2 and Figure 2) and in the three sites burned within a year of our sampling (Figure 3). PM10 emissions were no different on the two fires that burned 5 and 3 years prior to our sampling than their neighboring unburned treatments (Figure 3).

4.1.3. Sediment Supply and Erodibility

During the first ramp portion of the PI-SWERL tests \( (u_* = 0.09–0.39 \text{ m s}^{-1}) \) all study sites, burn treatments, and microsites demonstrated a comparable small peak in mean emission rate that ranged from slightly less than 10 to slightly more than 100 \( \mu g \text{ m}^{-2} \text{s}^{-1} \) (Figure 4). The \( u_* \) at which dust emission was initiated (i.e., equivalent friction velocity at which mean PM10 emission rates initially rose to the peak during the first ramp) appeared comparable for all conditions we evaluated (site, burn treatment, and microsite), and occurred in the small range of ~0.15–0.18 m s\(^{-1}\). Mean emission rates then decreased during the first step (~120–180 s into the test; \( u_* \) held at 0.39 m s\(^{-1}\)) suggesting that transport became limited in supply of erodible sediment, again similarly for all conditions evaluated.

During the second ramp \( (u_* = 0.39–0.55 \text{ m s}^{-1}) \), the rise to peaks in mean PM10 emission rates appeared to be initiated at \( u_* \) that ranged from ~0.42–0.45 m s\(^{-1}\). At the transition from the second ramp to the second step, mean emission rates for the burned undershrub microsites at the two most recent fires (Sand Hollow and Samaria sites) continued to rise whereas rates for the other sites, burn
treatments, and microsites initially rose and then declined (Figure 4). Supply limitation was evident for all conditions, with the exception of burned undershrubs at Sand Hollow and Samaria, during the second step ($u^*$ held at 0.55 ms$^{-1}$).

During the third and final ramp ($u^* = 0.55$–0.69 m s$^{-1}$), the rise to peaks in mean PM10 emission rates appeared to be initiated at $u^*$ that ranged from ~0.58–0.60 m s$^{-1}$. During the final step ($u^*$ held at 0.69 m s$^{-1}$), burned undershrubs in particular appeared to have abundant sediment supply at Samaria and Sand Hollow, and to a lesser extent at Noman and Moonshiner. Differences in mean emission rates for burned and unburned microsites were very pronounced during the final step, particularly for undershrub microsites, which had 2–3 orders of magnitude greater rates

Figure 2. Mean mass of PM10 emitted from PI-SWERL tests averaged by microsite and burn treatment for all study sites combined. Means with different letters indicate statistically significant differences at a significance level of 0.05.

Figure 3. Mean mass of PM10 emitted from PI-SWERL tests averaged by burn treatment and study site. Means with different letters indicate statistically significant differences at a significance level of 0.05.
Figure 4. Results of PI-SWERL tests showing mean rates of PM10 emission determined by microsite, burn treatment, and site. Means and standard errors are calculated with $n = 4$ PI-SWERL tests.
of PM10 emission after burning (Figure 4). The Clover site that burned 5 years prior to our study was an exception because the mean emission rates were very similar for burned and unburned undershrub microsites for the higher range of $u_*$ (Figure 4).

4.2. Wetted Surfaces

Similar to the measurements on non-wetted surfaces (e.g., Figure 4), more than one value of equivalent friction velocity at which PM10 emission was initiated was often apparent during an individual measurement, and supply limitation was sometimes evident in data plots of PM10 emission rates for wetted surfaces (individual data plots not shown). Values of equivalent friction velocity at which PM10 emission was initiated and rose to a peak were apparent during the first two ramp portions for all measurements, and were identifiable during the third ramp portion in five of the nine measurements, for example. Supply limitation was evident during the first step portion of all nine measurements (i.e., decrease in PM10 emission rate), and in the second step portion for five of the measurements, and during the third step portion for just one of the measurements.

Water potential of the top 1 cm of the soil ranged from −150 to 0 MPa (gravimetric water content ranged from 3 to 19%) among the nine wetted surfaces. Total mass of PM10 was moderately and negatively related to water potential, for the experimentally wetted plots (Figure 5). Total mass PM10 was strongly and negatively related to $u^*_{crit-PISWERL}$ (Figure 5). However, the relationship of $u^*_{crit-PISWERL}$ with water potential was statistically weak ($y = 0.001x + 0.59, R^2 = 0.30, p = 0.13$). The relationship of the maximum total flux of PM10 with water potential ($y = -1.8x + 1.4, R^2 = 0.59, p = 0.02$) and $u^*_{crit-PISWERL}$ ($y = -1414x + 874, R^2 = 0.84, p = 0.0005$) were similar to the relationships described for total mass PM10 with these variables.

5. Discussion

5.1. Fire, Microsites, and Time: Naturally Dry Surfaces

Dust emissions were substantially greater on the burned compared to unburned sites we evaluated on the Snake River Plain, due most apparently to erodible sediment supply. The abundance of erodible mass on these burn sites was much greater for undershrub in comparison to interspace microsites, and there was no variation in dust emissions among microsites in unburned sites. We examined a range of wildfire dates spanning 2005–2010, and time since fire appeared to be an especially important factor. PM10 emissions and supply were much greater for the more recently burned (<1 year) surfaces than neighboring unburned treatments, whereas there were no differences in these variables on sites that had several years since burning.

Our interpretation of time-since-burning effects relies upon the assumption that space can be substituted for time, which requires additional assumptions that the burned surfaces experienced similar histories with regards to ecosystem properties affecting erosion such as soil weathering and vegetation change. Soil texture and shrub ages (time for microsite development) varied among sites but did not appear to influence variability in PM10 emissions or our finding of the relative importance of time since burning. The largest and smallest quantities of PM10 emitted from burned sites were observed at the two sites that had the greatest proportion of PM10 in the surface soil (Samaria and Clover, respectively; see Figure 3 and Table 2), for example. Moreover, Sand Hollow had the lowest proportion of PM10 in the soil surface, yet burned surfaces at that site had the second largest emissions of PM10 from a burned site (Figure 3). On unburned surfaces, there were no differences in PM10 emissions among sites, despite the fact that mean shrub ages varied among sites.

The wide range of shrub establishment dates (5–50 years) indicated that our data set encompassed a robust range of time since previous disturbance, and hence a range of time for the development of soil under shrubs. The resultant data set was reasonably representative of sagebrush steppe landscapes for this region, considering previous studies of shrub recovery and fire return intervals. Postfire recovery of sagebrush was determined, for example, to occur within 30 years for at least one portion of the SRP [Sankey et al., 2008]. Presettlement fire return intervals were estimated to span from ~1 decade-2 centuries, with big sagebrush-dominated sites at the higher end of the range [Crawford et al., 2004]. Contemporary fire return intervals are expectedly shorter in sagebrush steppe that has been invaded by annual grasses such as cheatgrass, whereas the range is skewed toward longer return intervals in other locations due to fire suppression practices [Crawford et al., 2004; Baker, 2006].

Our finding of increased potential dust emission after wildfire suggests that shorter fire return intervals could increase erosive losses from sites. Results of our analysis indicated that recently burned undershrub microsites, in particular, have the greatest potential to contribute to total aeolian emissions in sagebrush steppe. These are important findings as wind erosion and dust plumes following wildland fires of increasing size and frequency have become a prevalent environmental issue in this cold desert biome [Sankey et al., 2009a, 2009b, 2010]. However, the fundamental spatial scale (shrub and interspace microsites) at which dust emissions and the supply of erodible mass vary on the ground has not been previously determined, and such information could generate insight on the mechanisms underlying increased erosion.

5.2. Sediment Supply and Erodibility: Naturally Dry Surfaces

Burned undershrub microsites clearly had the most abundant supply of erodible sediment, particularly at the greater $u_*$ examined. Interestingly there was little indication that the $u_*$ at which dust emissions were initiated differed substantially among sites, burn treatments, and microsites, given that this potential proxy of erodibility did not vary by more than 0.03 m s$^{-1}$ among all conditions. However, undulations (temporal variability) in the PM10 mean emission rate with increasing $u_*$ (Figure 4, both within ramp portions of the tests and among ramp and step portions) were observed during individual PI-SWERL tests. Similar temporal variability in PM10 emissions during individual PI-SWERL tests was reported by Sweeney et al. [2008] and Bacon et al. [2011]. Nickling [1988] previously suggested that variability in erodibility (specifically multiple threshold
friction velocities or \( u^* \) can exist for an individual surface that is actively eroding. Analogous examples of temporal variability have also been reported for surfaces undergoing erosion in field studies in a variety of environments [e.g., Wiggs et al., 2004a, 2004b; Stout, 2004, 2007; Ravi and D’Odorico, 2005] including cold desert sagebrush steppe [Sankey et al., 2009a, 2009b], though often at much larger spatial scales and under variable moisture conditions. The non-wetted surfaces we examined were small (i.e., PI-SWERL with effective area = 0.026 m\(^2\) was placed within patches <30 cm diameter) and dry. For the non-wetted surfaces, perhaps the temporal variability in dust emissions during individual PI-SWERL tests was also related to very fine (mm) scale vertical heterogeneity (micro-stratigraphy or horizonation) in properties of particle size and organic matter, which interact to influence aggregate stability, bulk density, crusting and structure at the soil surface.

**Figure 5.** Results of PI-SWERL tests performed on wetted surfaces burned by the Samaria fire. \( u_{\text{crit}-\text{PI-SWERL}} \) is the largest value of equivalent friction velocity at which a rise to a peak in instant flux of PM10 was initiated.
5.3. Soil Moisture

[31] Differences in near surface soil moisture and hydrologic characteristics, in general, are evident between microsite types in sagebrush steppe. A published time series of near surface (1 cm depth) water potential in sagebrush steppe microsites showed that extended periods of time (weeks-months) during which the soil surface was at most negative potential (dry) in the sagebrush steppe predominately occurred during summer-early fall seasons over one year of measurement [Flerchinger and Pierson, 1991]. Soil surfaces for both microsite types, for example, can spend extended periods (as much as 1–2 months at a time) during the summer at −150 MPa, and can demonstrate fluctuations from −150 to 0 MPa that are more frequent (daily to weekly) during late fall-spring [Flerchinger and Pierson, 1991]. Snow cover and wetter soil conditions, in general, are common during late fall-spring and can be intermittent or persistent. Following heavy, though not light precipitation events, near-surface soil-matric tension has been shown to decrease more rapidly for undershrub compared to interspaces in sagebrush steppe [Seyfried, 1991], suggesting that undershrub microsites tend to incorporate large quantities of surface water to lower depths more efficiently than interspaces. A set of infiltration measurements at 4 of our fire sites collected as part of this and an associated project [Hoover, 2010] indicated that infiltration rates ranged from 1 to 2 times greater on average for undershrub relative to interspaces on unburned and burned surfaces. Soils undershrubs often, but not always, have slightly higher water content than interspaces, and the magnitude of the differences can vary substantially throughout the year [Blackburn et al., 1990, 1992; Chambers, 2001; Davies et al., 2009]. After fire, however, the two microsite types often become more similar in water content and hydrologic characteristics [Pierson et al., 1994, 2001; Davies et al., 2009].

[32] The naturally dry hydro-climate conditions during which we performed the spatially extensive set of PI-SWELR measurements (i.e., non-wetted) were characteristic of conditions during which soil surfaces in this environment can be most susceptible to erosion [Sankey et al., 2009b]. The wetted burned surfaces at the Samaria site, furthermore demonstrated that environmental conditions that produce more moisture near the soil surface can coincide with lower potential dust emission. These findings are consistent with observations made at coarser spatial scales in burned sagebrush steppe [Sankey et al., 2009b] and a range of other environments, as soil and atmospheric moisture are often cited as factors controlling spatial and temporal variability in aeolian transport [Wiggs et al., 2004a, 2004b; Stout, 2004, 2007; Ravi and D’Odorico, 2005].

5.4. Biogeomorphic Insights

[33] Our findings offer insight into feedbacks between vegetation and surficial processes as well as the combined ecological and geomorphic role of bare-ground (i.e., interspace) soil surfaces in cold desert. While sediment transport rates have been previously described for burned and unburned sagebrush steppe, and were determined to differ by as much as two orders of magnitude [Sankey et al., 2009a], the extent to which the source of this sediment might vary at finer scales within the landscape has not been previously defined. Undershrub and interspace microsites are the fundamental scale at which soil surfaces vary in sagebrush steppe, and in this study we characterized the potential dust emission response that was unique to each of these microsite types that had and had not burned recently. Assuming that the two microsites types can each comprise roughly 50% of the soil surface in sagebrush steppe [Hoover, 2010], findings of this study indicate that the relative proportion of dust emission measured at coarser landscape scales that is derived from undershrub soil surfaces could be as much as 10–100 times greater than that derived from interspaces following fire.

[34] Why sediment supply might be enhanced by burning on sagebrush microsites in particular, is somewhat unclear. Fire generally does not have significant effects on soil texture and its spatial (i.e., microsite) patterning in sagebrush steppe [Pierson et al., 2001, 2002; Davies et al., 2009; Hoover, 2010]. Fire can reduce soil organic matter and carbon, and decrease the extent to which soil bulk density and infiltration rates differ between undershrub and interspace microsites in sagebrush steppe [Blank et al., 1994, 2003; Pierson et al., 2001, 2002, 2008; Davies et al., 2009; Hoover, 2010]. Direct effects of fire on soil aggregates and aggregate stability are not certain for sagebrush microsites and burned environments in general [Boix Fayas, 1997; Giovannini and Lucchesi, 1997; Garcia-Oliva et al., 1999; Mataix-Solera et al., 2002; Arcenegui et al., 2008; Varela et al., 2010]. However, fire can increase fine scale (mm-cm length scale) soil surface roughness which in turn promotes dust emission [Sankey et al., 2011]. Moreover, soil surface crusts which are common on bare interspaces and can increase the resistance of these microsites to erosion appear to persist following wildfire in sagebrush steppe [Hoover, 2010]. Perhaps aeolian sediment supply on microsites is influenced by the combination of increases in soil surface roughness that can be induced by fire and surface crustin interspaces that can be resistant to fire [Sankey et al., 2011].

[35] In contrast to findings on burned surfaces, we observed comparable potential dust emissions from interspace and undershrub microsites in sagebrush steppe that had not burned recently. It is unlikely that unburned-interspace microsites are subject to greater erosivity (near-surface wind flow) than unburned-undershrub microsites considering the extremely small fluxes of aeolian sediment that occur in undisturbed cold-desert landscapes [Sankey et al., 2009a, 2009b]. Bare soil is a commonly used indicator of ecological health in sagebrush steppe and is expected to correlate positively with increased wind and water erosion [Pyke et al., 2002]. However, the extent of bare interspace soil does not appear to be an indicator of dust emission and relative wind erosion potential on surfaces that have not burned recently, based on our findings in cold desert.

[36] The lack of variability in dust emission and relative wind erosion potential that we observed between the two microsite types on unburned sites might indicate that the role of aeolian processes in the formation and persistence of resource-rich undershrub and resource-poor interspace microsites is not as important in cold desert compared to warm desert [Schlesinger et al., 1996; Okin et al., 2009]. This could imply that aeolian processes have little lasting impact on the morphology of microsites and indicate that microsites develop due to, and are reinforced by, biological
and hydrological processes [Blackburn, 1975; Charley and West, 1975; Roundy et al., 1978; Wood et al., 1978, 1982; Doescher et al., 1984; Johnson and Gordon, 1988; Blackburn et al., 1990; Pierson et al., 1994, 2001, 2002, 2008, 2009; Goff et al., 1993; Schlesinger et al., 1996; Davies et al., 2007, 2009]. Alternatively, aeolian processes might operate in a much more complex manner in cold desert than the mechanism of erosion of interspaces and deposition on undershrubs that is commonly stated for unburned and undisturbed shrublands of the warm deserts [Schlesinger et al., 1996; Field et al., 2009a; Okin et al., 2009]. We propose that fire or another disturbance of vegetation at a coarse geographic scale is necessary for aeolian transport to significantly impact the biogeomorphicity of sagebrush steppe. This is analogous to increasing the connectivity of erodible surfaces as described by Okin et al. [2009]. Once a sagebrush steppe surface has burned, aeolian processes and microsites interact and potentially lead to a more complex biogeomorphic pattern. In support of this interpretation we observed that microsite differences and therefore spatial variability in potential dust emission and sediment supply were enhanced following fire.

6. Conclusion
[37] Spatial variability in dust supply and rates of emission was very prevalent at the fine spatial scale of individual undershrub and interspace microsites in sagebrush steppe that had been recently burned, but not in those that hadn’t been recently burned. Fire appeared to increase the supply of erodible sediment on undershrub microsites in particular. This could have important implications for restoration efforts in the sagebrush steppe where, for example, burned undershrub microsites can have greater success for reseeding efforts compared to burned interspaces due to the persistence of resource islands of soil nutrients following burning [Boyd and Davies, 2010]. Restoration efforts that attempt to leverage these microsite differences by primarily focusing reseeding efforts on undershrub microsites, for instance, might be less successful in landscapes that are prone to wind erosion. Wind could directly erode the seed bed and seeds, for example, as well as indirectly deplete the surface of nutrients and moisture adsorbed to soil particles. Our results could also have important implications for livestock grazing, because sagebrush densities and cover tend to increase with grazing pressure, such that sites can have a very high dominance of shrub and little herb cover [Anderson and Inouye, 2001]. Grazing has been linked to increased wind erosion in rangelands that have not burned recently [Belnap et al., 2009], and our findings suggest that sites that have been historically heavily grazed might have a much greater potential for dust emissions following fire. Therefore, while there are few management actions that can be implemented to reduce wind erosion after large fires, other than avoiding postfire soil disturbances, our findings suggest that management of vegetation before fire can affect wind erosion and dust emissions following fire.

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