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Dust emissions from undisturbed and disturbed, crusted playa surfaces: Cattle trampling effects

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ABSTRACT

Dry playa lake beds can be significant sources of fine dust emission. This study used a portable field wind tunnel to quantify the PM_{10} emissions from a bare, fine-textured playa surface located in the far northern Chihuahua Desert. The natural, undisturbed crust and its subjection to two levels of animal disturbance (one and ten cow passes) were tested. The wind tunnel generated dust emissions under controlled conditions for firstly an initial blow-off of the surface, followed by two longer runs with sand added to the flow as an abrader material. Dust was measured using a GRIMM particle monitor. For the study playa, no significant differences in PM_{10} concentration and emission flux were found between the untrampled surface and following a single animal pass. This was the case for both the initial blow-offs and tests on plots under a steady abrader rate. Significantly higher dust loading was only associated with the effect of 10 animal passes. In the blow-offs, the higher PM_{10} yield after 10 passes reflected the greater availability of easily entrainable fine particles. Under abrasion, the effect of the heaviest trampling increased the emission flux by a third and abrasion efficiency by around 50% more than values on the untrampled surface. This enhanced abrasion efficiency persisted for a 30 min period under abrasion before the positive effect of the disturbance was no longer evident. The findings highlight the role of a threshold of disturbance that determines if supply-limited surfaces will exhibit enhanced wind erosion or not after undergoing perturbation.

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1. Introduction

Existing as local sediment sinks, playas commonly contain a large supply of fine material and are potentially significant sources of dust in arid and semi-arid landscapes. Playas occur in a wide range of form and type, varying in their size, the geological setting they form in and their surface properties. It is these surface properties that fundamentally determine the wind erodibility of any dry or ephemeral lake. Erodibility is changeable over time and space and is controlled by key interacting factors such as sedimentology, chemistry and hydrology (e.g., Rosen, 1994; Gill, 1996; Bryant, 2003; Reynolds et al., 2007).

The development of surface crusts is an important characteristic of many dry lake playas. The high clay content of these environments encourages cohesion of fine particles, and in many cases, the role of evaporative salts can also contribute to a highly stable surface (Gillette et al., 1982; Langston and McKenna Neuman, 2005). The type of crust that forms and its essential properties vary according to factors such as clay content, wetting regime, presence of salts and proximity to groundwater (Reynolds et al., 2007). The broad range of interacting factors in crust development is demonstrated by the considerable variation in the type and strength of crusting that can be found even within an individual playa (e.g., Gillette et al., 2001). The surface properties of a playa, and the resulting crusts, directly affect the supply of fine-sized material available for deflation. Consolidation of surface sediments increases the threshold velocity required for particle entrainment and suspension. Since vegetation is commonly scarce on playas, surface crusts are a major source of protection against wind erosion, and disturbance of these stable surfaces is a vital control affecting dust emission from dry lakes (Gill, 1996).

Given their considerable potential as aerosol sources, many field studies have been conducted to understand playa wind erosion and dust emissions (e.g., Cahill et al., 1996; Gillette et al., 1997). Although direct (aerodynamic) entrainment of material from dry lakes has been demonstrated to be an active process on

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supply-limited playa surfaces (Macpherson et al., 2008), the role of bombarding saltating material on the surface is recognized as the primary driver for sustained release of fine material from these surfaces. This has been studied for soil crusts in general (e.g., Zobeck, 1991; Shao et al., 1993; Rice and McEwan, 2001) and also crusts in the specific context of playas (Gillette et al., 2001; Houser and Nickling, 2001a,b; Macpherson et al., 2008). A useful quantification of the role of abrasion in dust release from a surface is provided by an efficiency term (e.g., Shao et al., 1993). This efficiency has a basic ratio form of

$$F_d/F_s \tag{1}$$

where F_d and F_s are expressions of dust emission and saltation, respectively, both commonly presented as fluxes.

As a method to study wind erosion, the portable wind tunnel offers numerous benefits and has seen considerable usage on a variety of erodible surfaces (see Van Pelt et al., 2010 for an extensive review). Wind tunnels designed for use in field settings are especially well suited to investigations of dust emission from playa surfaces since they allow a controlled wind field to be applied to the surface while keeping the surface conditions intact, permitting genuine *in situ* sampling of the sensitive crust. Using a portable wind tunnel on a dry lake, Houser and Nickling (2001a,b) carried out extensive investigations on the relationship of PM_{10} emission (aerodynamic particle diameter < 10 μm) and saltation flux. More recently, working on a range of desert soils including playas with salt and colloidal crusts, Macpherson et al. (2008) used a portable tunnel to investigate aerodynamic entrainment of dust from supply-limited surfaces. The newly developed PI-SWERL instrument is another portable device that is successfully being used on playa surfaces to produce erodibility estimates (Etyemezian et al., 2007) validated using wind tunnel data (Sweeney et al., 2008).

With surface stability considered a critical control in the dust emission dynamics of dry lakes, the impacts of disturbance on crusts has been a research focus for understanding playa aeolian activity. Houser and Nickling (2001a) examined cattle trampled surfaces, categorizing them on estimated percentage cover disturbance and Macpherson et al. (2008) experimentally disrupted their study playa in order to measure the impact of such effects on dust release. Aside from physical crusts of playas, disturbance has also been investigated for the erodibility of biologically crusted desert soils with field wind tunnels (e.g., Belnap and Gillette, 1998; Leys and Eldridge, 1998; Belnap et al., 2007). In such experiments, the simulation of disturbance often involves an artificial agent, and although both are effective in disrupting consolidated surfaces and offering straightforward replication, quantifying the effect of a natural process of disturbance should also be of significant interest for understanding wind erosion.

The aim of this study was to investigate the effect of a realistic and systematic cattle-trampling disturbance on the dust emission characteristics of a crusted (clay rich) playa. The research used a portable wind tunnel to determine how two different levels of disturbance might change the dust emission potential of the playa surface.

2. Methods

2.1. Study site

The site selected for the study was a small (about 0.1 km^2) dry playa located on the toe-slope of a bajada within the USDA's Jornada Experimental Range near Las Cruces, New Mexico (Fig. 1). The Jornada Experimental Range is in the northern Chihuahuan Desert and has been the location of numerous wind erosion studies (e.g., Marticorena et al., 1997; Helm and Breed, 1999; Lancaster and Helm, 2000; Gillette and Chen, 2001; Li et al., 2007). From weather data measured using the USGS Geomet station during 1986–1997, mean annual precipitation was 212 mm with this rainfall being sufficient for vegetation growth, and wind speeds were calculated as being above the threshold for sand transport 8.3% of the time (Lancaster and Helm, 2000). Although many prior investigations were concerned with the role of vegetation in wind erosion (e.g., Musick and Gillette, 1990), the playa we used lacked vegetation. At the margins of the playa, however, there were numerous shrubs which had sand accumulations at their bases or even small coppice dunes (nebkha).

Soil surface characteristics of dry lake playas are highly variable. The soil surface of the playa in this study was clay-rich with strong physical crusting (Fig. 2). The properties of the crust and the similarities between study replication blocks are shown in Table 1. The texture was measured by the pipet method (e.g., Sheldrick and Wang, 1993). The surface sediments were classified as a clay loam with mean particle size class of 34% sand, 35% silt and 31% clay. Organic matter was determined from crust samples ground with a roller mill and then analyzed for C content using an Elementar Vario Macro C–N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ) operating at 550 °C. Dry aggregate stability was measured on 15–20 mm diameter clods using the vertical soil crushing-energy meter (Hagen et al., 1995). The clods for this test were collected from the uppermost 5 cm of the soil and therefore, do not only represent the crust surface. The most representative estimates of the strength of the crust surface came from 30 evenly spaced measurements made for each plot using a pocket penetrometer (Zobeck et al., 2003). The mean crust strength for the nine study plots was 6.41 kg cm^{-2} (standard deviation 1.12 kg cm^{-2}).

2.2. Field experiment

In an approximately 100 m by 65 m area on a flat part of the playa with visually uniform characteristics, three replication blocks were randomly located. Within each block, a level of treatment was randomly assigned to one of three parallel plots. The treatments applied were either (1) an undisturbed control surface (2) the surface after a single, straight perambulatory pass by an adult cow or (3) after ten walking passes by the cow. With the three trampling intensities replicated across each of the study blocks, the wind tunnel was used on nine plots in total.

The amount and type of animal disturbance simulated here typifies beef cattle impacts on soil surfaces. Cattle in transit tend to travel in a single line, and a disturbance level exceeding ten passes can easily exist in the formation of a trail. Frequency of trails, their degree of use, and branching depend on distance from water, placement of dietary supplements, topography, plant community physiognomy and patch structure of feeding and resting sites. The existence of trampling in similar vegetation types is demonstrated by Walker and Heitschmidt (1986) and Fredrickson et al. (2006). Playas, in particular, represent obstacle-free areas and Ganskopp et al. (2000) provides further analyses of least-effort cattle trail patterns. Although trail areas typically represent a small portion of the total range, they may be sources of fugitive dust emission or readily entrained sand that promotes abrasion of adjacent erodible surfaces. Further, the cattle may at different times of the day enter into behaviors that result in mechanical entrainment of dust from the surfaces where they gather. Temporally variable air quality problems exceeding USEPA limits have been documented in the vicinity of confined animal feeding operations and dairies.

A trained, 630 kg post-parturient cow with Angus–Hereford breeding was used for each pass on the non-control treatments. Portable livestock panel fencing was erected either side of the plots to ensure the cow remained in the plot as she was led straight

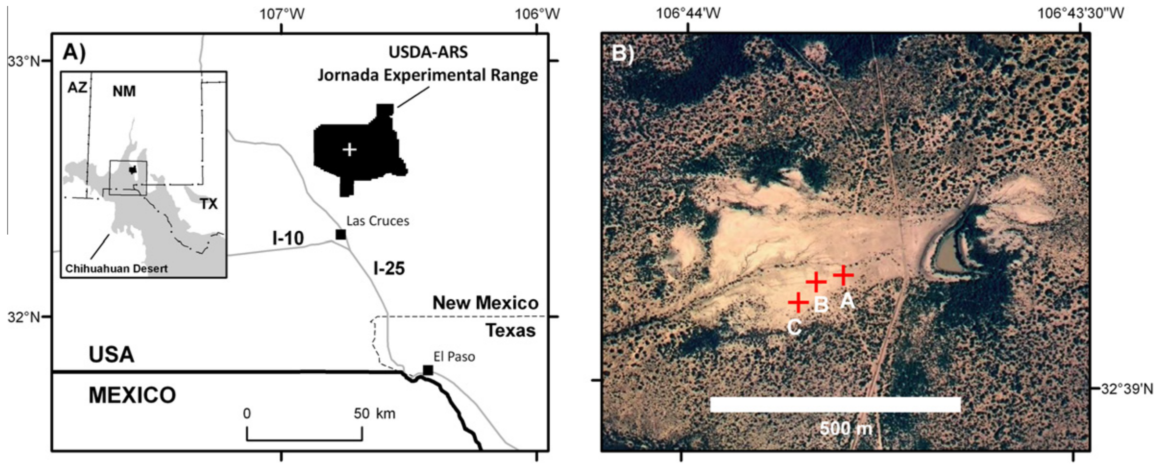

Fig. 1. (A) The location of the USDA-ARS Jornada Experimental Range. White cross indicates the location of the study playa within the range. Extent of Chihuahua Desert as defined by Schmidt (1979). (B) An aerial photo of the study playa from 1999. Crosses indicate the location of study replication blocks.

Fig. 2. (A) A cattle pass over a test plot section. (B) The wind tunnel set up on the playa.

Table 1
Crust properties by block (replication).

Block (rep)	Sand (%)	Clay (%)	Silt (%)	Texture	Organic matter (%)	pH	Dry aggregate stability† (J kg^{-1})	Crust strength‡ (kg cm^{-2})
A	38.0	34.2	27.8	Clay loam	1.7	7.9	705.4 (4.1)	7.11 (0.57)
B	32.4	28.5	39.0	Clay loam	1.9	8.2	609.8 (4.5)	6.9 (1.01)
C	31.8	29.3	38.9	Clay loam	1.8	8.1	996.4 (3.5)	5.31 (0.84)

† Values are geometric mean with geometric standard deviations in parentheses.
‡ Standard deviations in parentheses.

through by a handler outside the plot using a lead rope (Fig. 2A). The animal was trained to be led through the plots prior to the study so that she remained calm and to ensure the number of footfalls per pass were similar. Hoof size was measured by walking the cow over a similar soil that was wetted to leave a hoof-print where plaster casts of each foot could be obtained using a circular molding frame. For the four hooves, the mean width was 14.5 cm and heel-toe length 15.8 cm. The breed and size of the cow used in our study is typical of beef cattle commonly used on rangelands within the western United States.

The open bottom wind tunnel section was subsequently lowered over the disturbed plot soon after the cow had finished its passes. Foam padding on the bottom of the tunnel edges ensured the intact crust was not disrupted by placement of the wind tunnel and to establish a seal with the soil surface. Examples of typical surface disturbance associated with each of the levels of trampling are shown in Fig. 3. On the surfaces resulting from a single pass, the cow consistently delivered a straight line of hoof impacts. For these cases, the wind tunnel was carefully placed so that the straight line of hoof impacts was as centrally placed along the tunnel footprint as possible. In the single pass treatments, the cow also delivered a highly consistent number of hoof impacts for each pass, ranging between 8 and 9 (2.7–3.0 hooves m^{-2}) over the three replications. This produced a range of 14–17% surface disruption for single passes, as estimated by analysis of plot photos. The extensive surface disruption in the 10 pass cases meant hoof impact density could not be calculated, but the range of surface disruption was 74–88%.

2.3. Instrumentation

Elements of the design and performance of the wind tunnel used in our study are described in detail by Van Pelt et al. (2010). Airflow through the tunnel is generated using a hydraulically controlled push-type centrifugal fan (1 m diameter), with the flow passing through a tunnel 1 m high by 0.5 m wide, for a

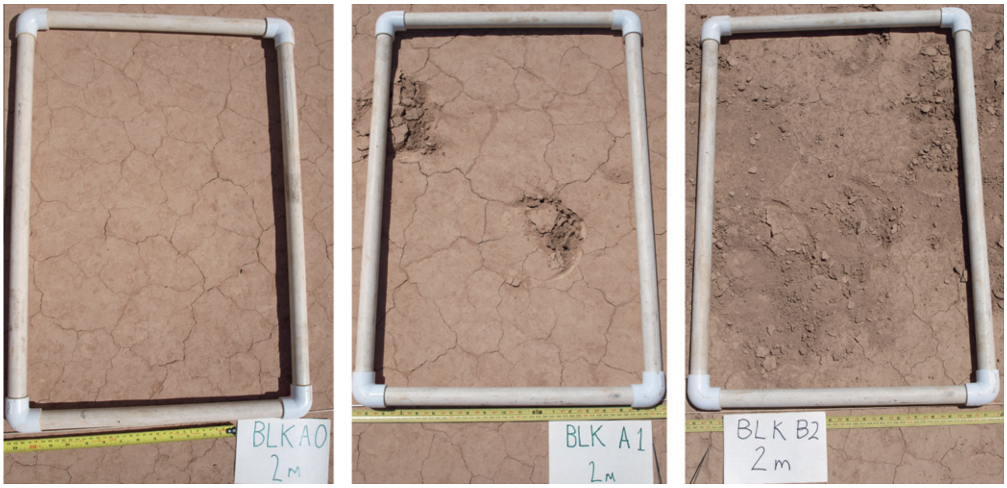

Fig. 3. Typical playa surfaces at 2 m into the wind tunnel open floor section for zero cattle passes (left), one pass (middle) and 10 passes (right). The frames are 65 cm by 45 cm.

total length of 8 m (Fig. 2B). Of this overall length, the working section open to the soil surface makes up the last 6 m. One meter upwind of the soil surface's start, feeder tubes allow abrader sand to be input from a hopper to a sandpaper-covered portion of floor. The input rate of abrader is fixed at 0.0145 kg m^{-1} s^{-1}, a rate comparable to that used in several laboratory-based wind tunnel abrasion studies (e.g., Zobeck, 1991; McKenna Neuman et al., 2005). The abrader material used was well-sorted fine sand (86.6% of mass between 106 and 500 μm) that was largely dust free (0.03% <10 μm) (see Van Pelt et al., 2010).

Prior to the current study, a flow conditioning section in the upwind part of the tunnel was calibrated experimentally so that a known velocity profile existed in the tunnel for a target wind velocity achieved at one height. Mesh screens in the conditioning section established a velocity profile in the tunnel that replicated the structure of near surface velocity previously observed during a natural wind erosion event (Stout and Zobeck, 1996). This known wind speed profile existed when a mean velocity of 12.6 m s^{-1} was achieved for a fixed point 0.5 m above the surface midway along the length of the tunnel. For all runs with the tunnel, subsequent to the initial run for each plot when the flow was brought up to the target 12.6 m s^{-1}, the dust monitoring experiments were conducted under the same velocity profile.

A vertically integrating slot sampler 1 m high (the entire height of the tunnel) with an opening 3.25 mm wide sampled sediment in suspension as well as material moving by saltation and creep at the center of the tunnel exit. The slot sampler was aspirated by suction fans at a rate to achieve a best possible isokineticity with the free stream of the wind tunnel at its steady experimental velocity (Van Pelt et al., 2010). For dust sampling we used an optical particle counter (GRIMM Technologies v1.108, GRIMM GmbH) located in the sampling pipe above the trap and by trapping aerosols drawn by the aspiration onto two 20 × 25 cm glass fiber filters. The GRIMM instrument has been used in other wind erosion studies (e.g., Funk et al., 2008) and works on the principle of laser scattering to provide counts of the number of particles per liter in 15 size bins (across the range 0.3–25 μm) for 6 s intervals. Particulate matter with a mass median aerodynamic diameter of less than 10 μm pose health risks and are considered by regulatory agencies in air quality standards (e.g., Cahill et al., 1996; Zobeck and Van Pelt, 2006).

To calculate the mass of PM_{10} for deriving the different dust fluxes examined, the total volume of particles in all GRIMM size bins <10 μm was first determined. This was calculated from the product of the mean volume of each aerodynamic diameter size bin and the number of particles in that bin, summed for all bins <10 μm. The product of total volume and assumed particle density (2.65 g cm^{-3}) yields the total mass of particles <10 μm. To produce the emission rate from the surface (mg m^{-2} s^{-1}), the <10 μm mass was divided by the maximum potential source area (the wind tunnel footprint of 3 m^2) and for the 6 s sampling interval. This yielded a mass per unit surface area, per unit time (Macpherson et al., 2008). For horizontal dust flux, Q_d, this was the mass of PM_{10} sampled per unit width, per unit time, equivalent to the saltation flux (Q_s) for trapped sediment >106 μm (see below).

Insufficient data were available to conduct a systematic removal of ambient dust levels from the results, so the data presented here include the background component. From short GRIMM readings taken before the wind tunnel tests, however, it was ascertained that baseline aerosol values were negligible, and the similar ambient conditions between runs ensured background levels were consistent (Table 2). Although instances of localized dust raising were seen on the playa e.g., dust devils, downdrafts, these did not occur during periods of active wind tunnel measurements. For the filter papers, samples were punched from the glass fiber papers and trapped sediment was loosened by sonic agitation.

Table 2
General meteorological conditions for the periods the wind tunnel was in operation across the consecutive study days. Data from the Jornada Long Term Ecological Research (LTER) project meteorological station, located approximately 15 km south west of the playa experiment site.

Date	Replication and number of passes	Mean temperature (°C)	Mean relative humidity (%)	Maximum 1 min wind speed (m/s) at 3 m height
13th July 2009	A0, B0	36.5	12.4	4.7
14th July 2009	C0, A1	36.6	13.6	5.7
15th July 2009	B1, A10, B10	36.2	14.7	3.8
16th July 2009	C1, C10	34.8	19.8	5.1

Agitation occurred for 2 min in methanol lithium chloride electrolyte using a Bransonic 1510™ ultrasonic bath. The sediment sample was subsequently run in a Coulter Multisizer 3™ in order to determine the percentage of PM_{10} material, which was then applied to the known mass on the filter papers. The air volume passing through the filters during each run was determined from the mean velocity in the sampling pipe, as recorded by a pitot tube reading to a datalogger.

The saltation and creep load was collected in a removable trap in the base of the slot sampler and was emptied at the end of each run. These samples were sieved to retain the sand sized fraction so all saltation fluxes (Q_s, g m^{-1} s^{-1}) were calculated using the trapped mass >106 μm. Rigorous calibration testing prior and subsequent to the fieldwork determined the trap was 73% efficient in the capture of saltation. Saltation fluxes measured in the study were adjusted to account for this. The sampler efficiency was determined by introducing a known amount of abrader into the tunnel and calculating the amount captured by the unit width of the vertical slot sampler, assuming the abrader was uniformly distributed across the wind tunnel (Van Pelt et al., 2010).

The wind tunnel runs were conducted over four consecutive days with similar daytime temperatures, low humidity and ambient wind speeds (Table 2). All study plots were subjected to an identical series of wind tunnel runs. After the tunnel was put in place on the plot, an initial run of 5 min was conducted. Within this run, the flow was initiated in the tunnel and then brought steadily up to the 12.6 m s^{-1} target velocity, a process which typically took around 1 min. At the end of the initial run, the trap was emptied and filter papers changed rapidly while the target flow in the wind tunnel was maintained. The second measurement run therefore required no speed up and lasted for 30 min. During this run, abrader sand was introduced to the surface from the feeder pipes and the flow velocity was held constant. After collection of the sampler trap and filters, a third and final 10 min run, also with abrader and steady target velocity, was conducted. From prior testing with the wind tunnel, for all soils previously examined, a relatively steady state of emission was recorded after 30 min of abrasion. The subsequent 10 min sampling run was intended, therefore, to sample this long term emission rate. This was the dust emission which might be expected during a sustained wind erosion event, with saltating material active on the surface. The abundance of sand at the margins for saltation over the playa during erosion events ensured the addition of abrader in the experimental runs was realistic.

Statistical analyses were performed using procedures of the Statistical Analysis System v9.1 (SAS, 2002). Analyses of variance of the dependent variables were performed using Proc Mixed with reps within trampling levels as a random effect. Statistical significance tests were performed at the P (probability) < 0.05 level of significance.

3. Results

3.1. PM_{10} concentration

Values of PM_{10} dust concentrations derived from the GRIMM show the different effects of trampling intensity (Fig. 4). For Run 0, the initial blow -off with no abrader added, although the dust emitted almost doubled between zero trampling and one pass of the cow, this disparity was not statistically different. The greater Run 0 concentration measured after 10 passes, however, was significant. When considering the differences between the experimental runs on the undisturbed playa only (0 animal passes), the effect of introducing saltation is apparent. The dust concentration from the initial blow-off on the untouched consolidated surface was 0.95 mg m^{-3}. Addition of abrader in Run 1 led to a fourfold increase in concentration of PM_{10}.

For the surface after one cow pass, the amount of dust doubled with the addition of saltation (Run 1) but the difference was not found to be significant at P < 0.05. This was due to the relatively increased dust concentration in Run 0 which resulted from the animal pass. Comparing the abraded Runs 1 and 2 after one pass, the single pass did not generate greater dust concentrations when compared to the undisturbed playa surface. The disturbance by 10 passes, plus the addition of saltation (Run 1), however, did enhance dust emissions significantly. Expectedly, the maximum dust concentration of any run was observed for the 30 min abrader period after 10 passes (7.23 mg m^{-3}). For the highest trampling intensity, the difference between the Run 0 and 1 concentrations was also

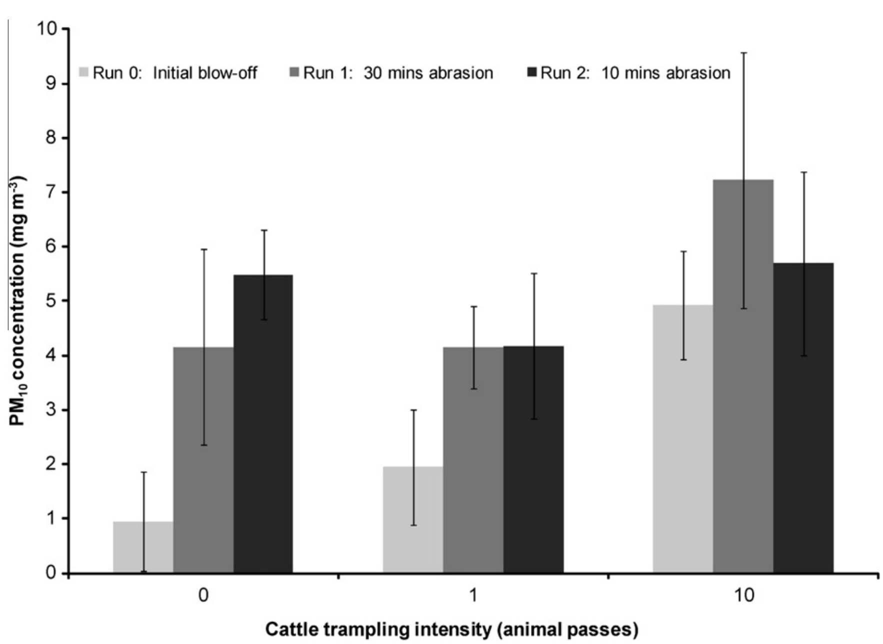

Fig. 4. Mean PM_{10} concentration for each wind tunnel test run and surface trampling intensity. Error bars express standard error.

not significant at $P < 0.05$. This again reflects the higher dust concentration in the initial blow-off caused by severe disturbance of the surface crust.

Considering each level of disturbance individually, the dust concentrations from Runs 1 and 2 could not be separated in each trampling intensity case. This indicates that for each disturbance, the dust emission was maintained across the two saltation runs, or, for the entire duration that each surface was abraded. The overall pattern of PM_{10} concentration determined from the GRIMM output in Fig. 4 was confirmed in the estimates using the glass fiber filters. The variability in the concentrations derived from the filters was considerably greater, so that only the GRIMM derived values are presented here. The variability in filter values was assumed to be related mostly to filter handling difficulties e.g., samples accidentally losing mass during placement in anti-static storage bags.

3.2. Surface emission rate

The mean rate of PM_{10} emission from the test surface area (mg m^{-2} s^{-1}) for each 6 s interval of GRIMM sampling reveals greater detail concerning the behavior of dust emission and the effect of trampling (Fig. 5). During the initial blow off, the dust emission from the undisturbed, crusted playa surface was consistently low (0.07 mg m^{-2} s^{-1}) and close to background levels (Fig. 5A). For both the 1 and 10 pass cases, sudden increases are seen in emission rate at or just after 30 s. The single pass then results in relatively elevated emission for the first 180 s of the run, after which the flux approaches that observed for the undisturbed playa surface. For the plots that underwent 10 cow passes, the early dust emission is greater still and displays wide scatter for 120 s before beginning to tail off. During the final 90 s of the run, although low, the PM_{10} emission rate after 10 passes remains double that of the control and single pass surfaces.

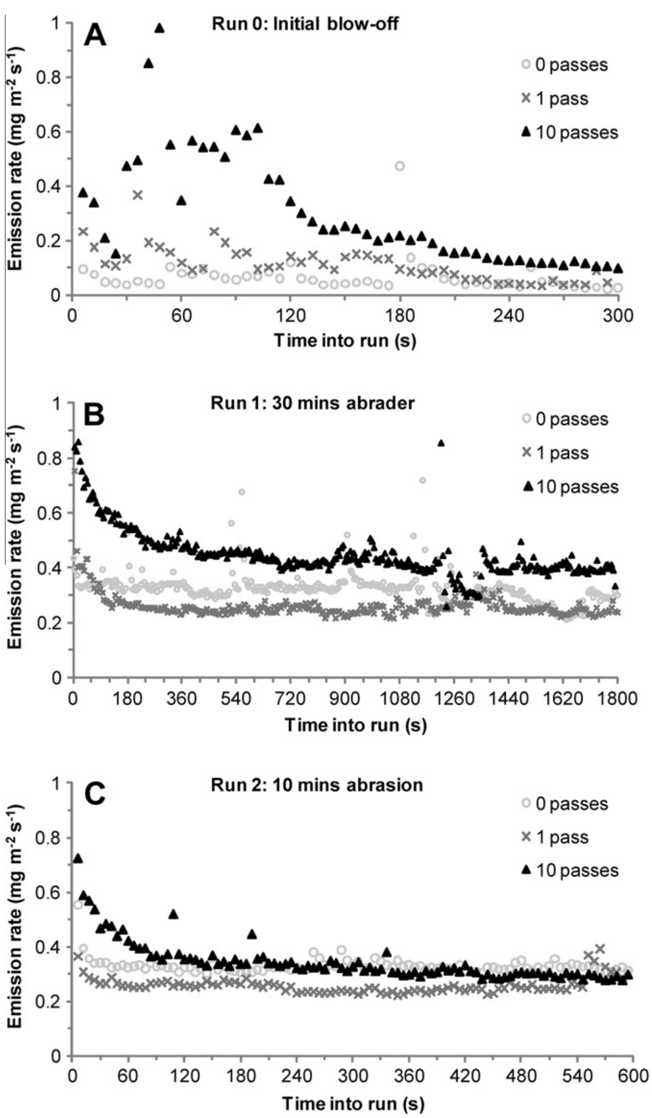

Fig. 5. Emission rate of PM_{10} from the surface for (A) Run 0, initial blow-off (B) Run 1, 30 min of abrader (C) Run 2, 10 min of abrader. Note same vertical scale for all runs.

Run 1 involved the addition of a constant flux of abrader to the different surface treatments (Fig. 5B). On the undisturbed playa, the added saltation resulted in a relatively steady PM_{10} emission from the surface. At 0.3 mg m^{-2} s^{-1} this was around four times the flux from the undisturbed surface under no abrader. Occasional, short duration emission peaks (<25 s) through the time series might represent small scale failures of the surface exposing unconsolidated sediment, though inspection of the plot surfaces after the run did not suggest this was due to removal of individual crust sections. For the playa surface under abrasion following one pass of the cow, noticeably elevated emission rates are seen at the start of the run within the first 100 s. After the early period, dust emission drops to a consistent rate that is similar to, and in fact less than, the undisturbed surface. For the treatment with 10 passes there was increased dust emission for a longer period at the start of the run, occurring through approximately the first 270 s. After this, PM_{10} emission was largely steady in the region of 0.4 mg m^{-2} s^{-1}, a rate around a third higher than from the undisturbed playa under abrasion.

For the final run, a 10 min period of abrasion (Run 2), the emission rate from the untrampled surface was again briefly high for the opening 30 s during which the rate decreased toward the steady value evident in the previous abrasion Run 1 (Fig. 5C). On the surface after a single pass, the pattern was similar. A steady emission rate developed that was once again lower than the sustained value from the non-trampled surface. One of the replications of Run 2 on the single pass surface was not included in the mean time series due to battery problems with the GRIMM instrument. The surface created by 10 passes again had a longer initial period of elevated PM_{10} emission rate (lasting 90 s). After this, however, the dust flux from the surface became steady at an emission rate comparable to that from the abraded undisturbed playa.

3.3. Saltation flux and abrasion efficiency

The time series of emission rates show the emergence of a steady dust flux for each of the surfaces during each sampling run (Fig. 5). The final third of each run was deemed to adequately represent this sustained dust flux, and the mean steady emission rate for each surface was thereby calculated from the last 100 s for Run 0, the last 600 s for Run 1 and the last 200 s for Run 2. To compare the abrasion efficiency of the surfaces following the different levels of trampling, the ratio of the horizontal PM_{10} (Q_d) and saltation (Q_s) fluxes in equal units of g m^{-1} s^{-1} was determined (following Shao et al., 1993 who termed the ratio "bombardment efficiency"). The horizontal PM_{10} flux used in this ratio was that derived from the final third of each run, as detailed above. When each surface received abrasion, this best represented the Q_d which developed under steady saltation.

With no abrader added, the Q_s values for Run 0 reflect the amount of saltation and creep-transportable material available at the surface for each level of trampling (Fig. 6). The single cow pass did not result in a saltation flux significantly greater than for the untrampled playa for Run 0, but the impact of ten passes did. For the runs where abrader was applied at a rate

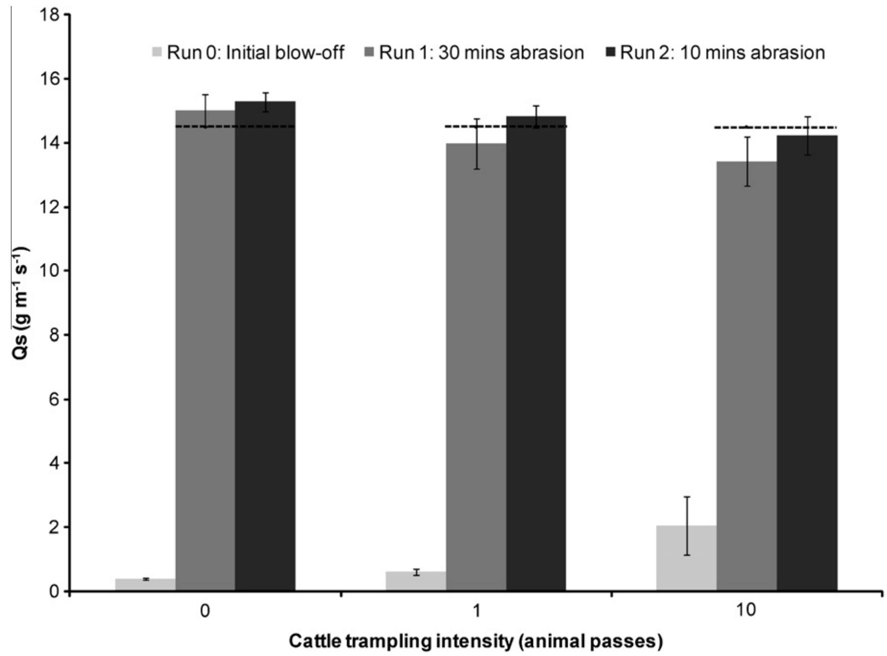

Fig. 6. Saltation flux (sediment > 106 μm) Q_s for each wind tunnel test run and surface trampling intensity. Error bars express standard error. Dashed line represents equivalent flux from the constant abrader input.

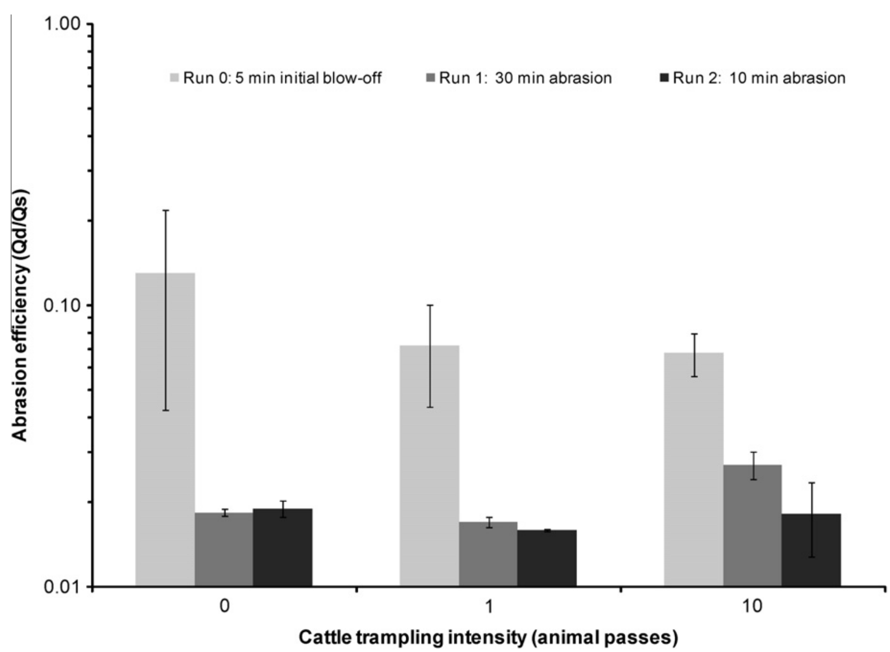

Fig. 7. Mean abrasion efficiency for each wind tunnel test run and surface trampling intensity. Error bars express standard error.

equivalent to 14.5 g m^{-1} s^{-1} (marked by dashed lines in Fig. 6), a component was evidently contributed to the saltation flux by erosion of the undisturbed playa surface. This is evident from the fluxes of Runs 1 and 2 on the undisturbed surface, which are in excess of the input abrader rate. Both of the disturbed surfaces exhibited Q_s less than the input flux for Run 1, indicating the deposition of some abrader sand due to the increased surface roughness after trampling. Inspection of the plots after saltation runs visibly confirmed white abrader sand had been trapped in disturbed surface areas during the tests e.g., in hoof prints. The saltation transport in Run 1 for the two disturbed conditions indicates that loss of abrader through surface deposition exceeds the mass of saltation material entrained after the effect of the animal. The increase in Q_s for Run 2 over Run 1 after one or 10 passes suggests that the greater surface roughness was reduced over time under abrasion. Erosion of protruding displaced sediment and depositional infill would cause this, but the observed Q_s increase was not statistically significant. Overall, there were no significant differences in the saltation flux values between the single and ten pass disturbance levels.

Fig. 7 shows the abrasion efficiency of the differently trampled surfaces for the three experimental runs. In the initial blow-off runs, only very small amounts of saltation flux were measured (Fig. 6) making the abrasion efficiencies for these runs considerably greater than the tests with the constant abrader flux. The ratio of dust production to saltation was greatest for the undisturbed surface, with the disturbed surfaces exhibiting alike efficiencies.

On the undisturbed playa, the similar abrasion efficiency in the Run 1 and 2 saltation periods indicates the efficiency of the stable surface remained steady and did not change throughout the total 40 min of abrasion. Abrasion efficiency was also consistent between Run 1 and 2 for the one pass plots. This indicates that, for a given amount of saltation, the single pass level of disturbance did not generate more dust than the untrampled surface. A significant increase in abrasion efficiency is evident, however, for the Run 1 tests on the 10 pass surface. Here the dust to saltation ratio is around 50% greater than for the other surfaces. By Run 2 on the heavily disturbed plots, whilst variability was high, the mean efficiency was comparable to both the control and single pass cases. Despite the fact the dust emission rates presented here are somewhat lower than those in the comparable Houser and Nickling (2001a) data, the abrasion efficiency ratios agree well with the range Houser and Nickling (2001b) found for their wind tunnel work on a playa.

4. Discussion

4.1. Effects of trampling on emission during initial blow-offs

The difference in PM_{10} concentrations between the initial runs on the three surfaces clearly demonstrates that dust loading in the blow-off runs is driven by the amount of available suspendable material (Fig. 4). The variability in concentrations for Run 0 is also a consequence of different amounts of loose erodible material on the surface. As other studies have established, a consolidated, crusted playa represents a classic sediment supply-limited surface, and varying degrees of disturbance directly alter this limited state (e.g., Houser and Nickling 2001a; Macpherson et al., 2008). In all treatments of the current playa, emission during Run 0 was restricted to a pulse of sediment at the start of the run, and the time series data illustrate the eventual exhaustion of suspendable fines which suppresses the release of dust (Fig. 5A). Since the flow was accelerating in the first minute or so of Run 0, as speed was increased from near zero toward the target velocity, the sudden increases in emission rate measured just after 30 s for the one and 10 pass cases appear to represent the threshold of dust entrainment (around $7.5\ \mathrm{m\ s^{-1}}$). The relatively little sediment generated after one pass results in a very brief peak. The greater amount of loose material produced by 10 passes, however, sustains enhanced blow-off emission for a further 90 s.

After 10 passes of the cow, an emission rate discernible from the background was maintained until the end of the blow-off run. This indicates that the highest level of disturbance created enough sediment supply to sustain at least some aerodynamic entrainment throughout the entire 5 min test period (Loosmore and Hunt, 2000). The associated flux, however, was very low. This reinforces the fact that disturbance alone does not nourish prolonged, significant PM_{10} emission from such clay rich playa surfaces. Houser and Nickling (2001a) also observed that even unconsolidated playa sediments require saltation impacts for sustained dust emission. In some crusted desert soils with higher sand contents, disturbance can lead to increased sand availability and the occurrence of effective abrasion (e.g., Belnap and Gillette, 1997). With the structure of the playa sediment in this study, however, this effect was not seen to occur.

Interesting comparisons can be made between the Run 0 blow-off cases here and the extensive tests on aerodynamic entrainment from desert surfaces conducted by Macpherson et al. (2008). They identified three signature types of emission based on characteristic patterns of dust release over time. Fig. 5A shows the zero and single pass surfaces with small secondary peaks punctuating their descending limbs of emission. They are best described by the Type III classification of Macpherson et al. (2008; see also Sweeney et al., 2008). In their study, this pattern of emission was the most common. The pattern was found for both disturbed and undisturbed clay-crusted surfaces (similar to the Jornada case here) and shows evidence of sporadic aerodynamic release of dust from surfaces subjected to a low level of disturbance. Our 10 pass surface is more similar to the Type I pattern that Macpherson et al. (2008) describe since it exhibits constant emissive decline after a relatively long initial peak. Macpherson et al. (2008) found this type primarily on disturbed non-cohesive sediments, whereas in the current study, the sediments are strongly cohesive. The applicability of Type I to the treatment with 10 passes may be due to the greater disturbance generating sufficient non-cohesive sediment from the crusted playa. Although Macpherson et al. (2008) acknowledged that abrasion is the dominant mechanism for prolonged and high-yielding wind erosion events from playas, they stress that the process of aerodynamic entrainment from supply-limited surfaces may be under appreciated.

The abrasion efficiencies of the Run 0 blow-off periods were considerably greater than the ratios for when abrader was added (Fig. 7) which also agrees with findings from Macpherson et al. (2008). Measured Q_s values were very small in the blow-off runs (Fig. 6) and the efficiency of these runs reflects directly the availability of readily suspendable sediment and not, therefore, the process relationship between abrasive saltation and dust emission. The major determinant of dust emission in the blow-off case is the capacity of the surface to release fines (Nickling and Gillies, 1993). Interestingly, there was a decrease in abrasion efficiency after trampling for the Run 0 tests (Fig. 7). The Q_s measured in the Run 0 cases increased following any degree of disturbance, which has the effect of reducing the ratio of dust production to saltation. This seems in contrast to Macpherson et al. (2008) who showed abrasion efficiency increasing with disturbance in clay-crusted soil, an observation they attributed to changes in the capacity of the soil to emit dust. In our study, even though there is a greater saltation flux for Run 0 after 10 passes, it is not believed the greater PM_{10} observed for that blow-off is driven by the elevated Q_s. The decrease in abrasion efficiency with disturbance masks the increased emission that actually occurs with disturbance. This suggests the efficiency ratio term is less useful where Q_s values are very low.

In summary, for the blow-off tests on this study playa, the effect of a single cow pass produced a slightly increased dust yield from the surface which was not significantly greater than emission from the undisturbed condition, due to the variability of each treatment (Fig. 4). The positive effect of cattle passage on PM_{10} emission during blow-off was only significant following the highest intensity of trampling investigated.

4.2. Effects of trampling on emission under abrasion

Even though emission was seen to occur from the study playa due to aerodynamic forces alone, dust release from erodible surfaces is far more significant when saltation is present (e.g., Shao et al., 1993). On this playa, the total PM_{10} concentration from the undisturbed surface was four times greater when under abrasion (Fig. 4) and the emission rate around four times the unabraded rate (Fig. 5A and B). Where the aerodynamically driven emission is short-lived due to the relatively rapid removal of available entrainable material, the process of abrasion enables prolonged dust emission since the saltating impacts break particle bonds and thus continually generate suspendable sediment (Fig. 5C) (Houser and Nickling, 2001a).

Even under saltation, however, in this study, the disturbance caused by one cow pass did not significantly increase the PM_{10} emission from that of the pristine playa. The PM_{10} concentration observed for the longest test period with abrader (Run 1) was not significantly greater than the undisturbed surface until after the treatment of 10 trampling passes (Fig. 4). In accounting for this, it is notable that the surface after 10 passes had a statistically similar saltation flux to the single pass case (Fig. 6). This suggests that the increased dust release after 10 passes was caused by weakened resistance of fine textured sediment and greater availability of PM_{10}, as opposed to an increase in bombardment through disturbance liberating material to abrade. Abrasion efficiency has been found to be strongly related to PM_{10} availability, and a greater supply of fine sediment is generated by the trampling (Houser and Nickling, 2001b). The increase in efficiency for Run 1 after 10 passes represents, therefore, a fundamental change in the ability of the soil to emit dust, and shows how trampling alters the supply-limited nature of the surface (Macpherson et al., 2008). For this playa, the crust durability and strength of interparticle bonding meant that one cow pass did not result in sufficient weakening for an increased dust emission. This was the case even with the addition of a steady saltation flux.

Abrasion efficiency has been found to not necessarily increase with degree of surface disturbance (Houser and Nickling, 2001b), though other studies have found positive relationships between the two (Belnap and Gillette, 1998; Macpherson et al., 2008). In this study, although the abrasion efficiency was similar for the zero and one pass tramping conditions, it was statistically greater under 10 passes for Run 1 (Fig. 7). Enhanced entrainability of PM_{10} resulting from the highest level of disturbance was found to exceed any negative effect on emission caused by reduced saltator impact velocity or energy transfer. These twin effects, caused by reduced surface elasticity of the disturbed patches, have been suggested as the explanation for why disturbance to a surface can lead to a reduced efficiency ratio (Houser and Nickling, 2001b).

Another observation is that the effect of the surface disturbance was seen to diminish over time. The time series plots show that within 180 s of Run 2, the measured dust flux from the 10 pass surface had fallen to values comparable with the untrampled case (Fig. 5C). This is also reinforced in the abrasion efficiency after 10 passes. Following the maximum observed efficiency in Run 1, a decrease was exhibited for Run 2 where Q_d/Q_s was similar to the undisturbed surface (Fig. 7). This indicates the end of the increased susceptibility to erosion, through generation of readily entrainable fines and weakened particle bonding, which the most intense trampling produced. Even though the effect of the disturbance no longer resulted in elevated emission at the end of the final testing period, Fig. 5C shows that the long term dust flux from the surface was maintained for as long as sand abrades over the playa (Houser and Nickling, 2001a). The impacts of the abrader continually act to make fine material available so that under abrasion, the surface is effectively in a supply non-limited state.

In the time series of emission rates, a comment ought to be made about the large values seen in the early stage of the saltation runs (Fig. 5B and C). Although the introduction of saltation would be expected to increase emission, the immediate response of the surface in terms of yielding dust and the absence of any lag time between the start of the abrader and the increased dust measurement seems unlikely. Houser and Nickling (2001a) for example show a more probable rise in dust concentration from background values to a peak value which occurs through the opening 10 s of their runs. One suggestion is that the GRIMM instrument in the current study might not have settled to the background level before the commencement of the abrader flux. For instance, the increase from a steady rate evident at the end of Run 1 to the high emission at the start of Run 2 for both the 0 and 10 pass surfaces is difficult to explain purely due to the erosion process. Cessation and then re-application of the abrader flux on the same surface under a steady flow should not create this effect, and it is more likely an instrument artifact. If there is some uncertainty about emission rates at the start of the abrader runs, there is far more certainty about the sustained emission rates that clearly emerge for each surface under saltation.

4.3. Thresholds of disturbance

For the playa in this study, there was no significant change in total PM_{10} concentration or emission rate from the surface between zero animal passes and the application of a single cow pass. This was the case both for runs where emission was driven by aerodynamic entrainment only and those with the addition of an abrader flux to provide bombardment. Sediment supply-limited surfaces are known to be significant dust sources and disturbance is a key factor in making them active emitters. The results presented here highlight the importance of thresholds of disturbance that determine whether a potentially emissive surface will be active, and the degree of disturbance necessary for increased wind erosion from a given surface. This concept is applicable to any sediment supply-limited surface. The threshold that exists for a surface is controlled by two factors; the nature of the disturbance agent and the many surface properties that determine the resistance to it. For a playa, surface properties show considerable heterogeneity over time and space, as driven by climatic, sedimentological, geochemical and biological conditions. This makes surfaces highly variable with time and between, or even within, individual landforms (e.g., Gill, 1996; Reynolds et al., 2007). With thresholds of disturbance for a surface proving changeable due to the numerous determining factors therefore, one consequence is that the effectiveness of a given perturbation in enhancing dust emission is highly difficult to predict.

5. Conclusions

This work employed a field wind tunnel in order to characterize the effect of a realistic, systematically controlled disturbance on fine dust emissions from a crusted playa surface. The study was concerned with a research question concerning how two levels of trampling changed the PM_{10} emission potential from a clay-rich dry lake. The logistical limitations of the fieldwork restricted the experiment to three replications of three conditions of the surface, but the data allow a series of conclusions to be drawn.

(1) On the study playa, for the initial wind tunnel tests which blew off the surface, the impact of a single cow pass did not significantly increase total PM_{10} concentration or the emission flux from the surface. Following 10 passes by the cow, however, dust emissions were significantly greater. Dust loading during blow-off periods without active abrader reflects directly the amount of readily entrainable fine dust generated by the disturbance.
(2) During the tests with a constant abrader input added, the pattern was the same, with a significant increase in PM_{10} yield only occurring following 10 passes. There were no differences in the abrasion efficiency ratio (representing dust production for a given saltation rate) between all abrader runs on the control and single pass surfaces. After 10 passes, efficiency was around 50% higher. Since Q_s was not greater in

this case, dust flux increased likely by the trampling exposing weaker bonded sediments vulnerable to bombardment. The positive effect of the greatest disturbance diminished over time since the elevated efficiency was only seen during the first 30 min period of abrasion.

(3) Without saltation, there was some evidence of aerodynamic entrainment occurring on all the differently conditioned surfaces, which was of a relatively very small magnitude. The application of a constant abrader flux led to a fourfold increase in total PM_{10} concentration and a similar increase in the measured steady state of surface emission flux.

(4) Abrasion efficiencies were significantly greater for the blow-off runs than the tests with abrader, but this was a consequence of very small saltation fluxes in the former. The efficiency ratio might be misleading where Q_s is low since dust emission is not driven by the bombardment process in these cases, rather it is determined by availability of easily suspendable material.

This study stands as another application of a portable wind tunnel to a potential dust source land surface, to help better understand the controls on its emissivity. The work reinforces the established idea of crusted playas behaving as supply-limited surfaces and the different levels of trampling applied here were seen to alter this limited state to varying degrees. The fact that emission was not found to be increased after the lightest level of disturbance highlights the importance of thresholds of disturbance on such supply-limited surfaces. This threshold is related to the response of the surface to a particular perturbance, and represents the level of disturbance required for accelerated wind erosion to result. If the effects of disturbances on supply-limited surfaces are to be accurately simulated, the varying nature of the disturbance threshold over time and space will need to be recognized within predictive attempts.

6. Disclaimer

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by US Department of Agriculture. USDA is an equal opportunity provider and employer.

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