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Contemporary and future dust sources and emission fluxes from gypsum- and quartz-dominated eolian systems, New Mexico and Texas, USA

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ABSTRACT

Recent research on dust emissions from eolian dunes seeks to improve regional and global emissions estimates and knowledge of dust sources, particularly with a changing climate. Dust emissions from dune fields can be more accurately estimated when considering the whole eolian system composed of active to stabilized dunes, interdunes, sand sheets, and playas. Each landform can emit different concentrations of dust depending on the supply of silt and clay, soil surface characteristics, and the degree to which the landforms are dynamic and interact. We used the Portable In Situ Wind Erosion Laboratory (PI-SWERL) to measure PM10 (particulate matter <10 µm) dust emission potential from landforms in two end-member eolian systems: the White Sands dune field in New Mexico (USA), composed of gypsum, and the Monahans dune field in west Texas, composed of quartz. White Sands is a hotspot of dust emissions where dunes

and the adjacent playa yield high dust fluxes up to 8.3 mg/m^2/s. In contrast, the active Monahans dunes contain 100% sand and produce low dust fluxes up to 0.5 mg/m^2/s, whereas adjacent stabilized sand sheets and dunes that contain silt and clay could produce up to 17.7 mg/m^2/s if reactivated by climate change or anthropogenic disturbance. These findings have implications for present and future dust emission potential of eolian systems from the Great Plains to the southwestern United States, with unrealized emissions of >300 t/km^2/yr.

INTRODUCTION

Field measurements and model-based estimates of dust emissions from dune systems are difficult to characterize (Amit et al., 2014; Adams and Soreghan, 2020; Swet et al., 2020), confounding present and future contributions to atmospheric dust loading (Bullard et al., 2011; Crouvi et al., 2012). This is important to resolve because estimates of total atmospheric dust loading are wide-ranging and contain uncertainties associated with source areas and the processes driving dust emissions, limiting our understanding of the impacts of atmospheric dust on radiative forcing, biogeochemical cycles, extreme climate variability (Kok et al., 2021), and human health (Crooks et al., 2016). Sand dunes and sand sheets, though spatially extensive, have been largely ignored as significant dust sources because eolian sands typically contain <5% silt and clay that could become entrained as dust (Prospero et al., 2002). Laboratory and wind tunnel research on abrasion, the process of chipping, spalling, and grain coating removal of quartz sand, suggests that quartz-rich sand dunes are not major dust sources (Bullard et al., 2004; Adams and Soreghan, 2020; Swet et al., 2020), while other field research (Sweeney et al., 2011; Bolles et al., 2019) and remote-sensing measurements (Bullard et al., 2008; Lee et al., 2012) suggest that dunes and sand sheets containing even a few percent silt and clay can potentially produce dust over large areas and wide ranges of concentrations. This may be especially true in eolian systems with diverse landforms where saltation bombardment of sand on finer-grained soils, such as playas, results in high dust emissions (Bullard et al., 2011). Such is the case for the Bodélé Depression in Chad, where saltation bombardment and the disintegration of sand-sized aggregates composed of silt and clay result in one of the largest global sources of dust today (Bristow and Moller, 2018). Ongoing field characterizations of dust sources and emission potential are critical to enhance our understanding of the spatial and temporal variability in atmospheric dust loads (Bullard et al., 2011), which will lead to increased accuracy of dust models (Kok et al., 2021).

Our study provides insight on dust sources and ranges of dust emissivity for two end-member eolian systems: (1) White Sands dune field in New Mexico (USA), composed of gypsum sand (Mohs hardness = 2), and (2) Monahans dune field in west Texas, composed of mature quartz sand (Mohs hardness = 7; Fig. 1). These dune fields produce a range of dust emission potentials from active dunes and other associated landforms including vegetated dunes, sand sheets, interdunes, and playas. The White Sands area is considered to be a dust emission hotspot (Baddock et al., 2016). Hotspots dominate atmospheric dust loading in many arid environments because they are relatively flat and free of vegetation and rock cover, they lack surface crusting, and they have ample sediment supply—key properties that facilitate wind erosion (Gillette, 1999). Hotspots are typically located in topographic depressions, commonly associated with ephemeral or dry lakes and river valleys where sediment can be periodically replenished

(Prospero et al., 2002). The active Monahans dunes, on the other hand, emit low levels of dust; however, the stabilized dunes and sand sheets that surround the active dunes store silt and clay and could become dust sources if reactivated. Better knowledge of dust emission sources, variability, and fluxes at a landform scale may help to predict future dust emissions, particularly with the increased drought forecasted for the twenty-first century (Cook et al., 2020).

SETTING AND METHODS

White Sands eolian sand, composed of 95%–99% gypsum (Fenton et al., 2017), is derived from the deflation of beds of the former Pleistocene Lake Otero and ephemeral Lake Lucero, driven predominantly by southwesterly winds, generating eolian sand patches, sand sheets, protodunes, and dunes (Ewing, 2020). Dust storms are common from March to May (White et al., 2015), and daily eolian activity requires low humidity and extreme temperature changes that create atmospheric turbulence, resulting in winds that drive saltation and dust generation (Gunn et al., 2021). The Monahans dune sand is composed of 90%–95% quartz derived primarily from the Pecos River, with some input from the Blackwater Draw Formation, but with an ultimate source from the Triassic Chine Formation **[[Should this be the Chinle Formation?]]** (Muhs, 2004). Seasonal winds from multiple directions result in dune activity but minimal net migration (Muhs and Holliday, 2001). The areas of active dunes are surrounded by stabilized parabolic dunes, blowouts, and sand sheets.

Dust emission potential was measured in the field using the Portable In Situ Wind Erosion Laboratory (PI-SWERL**[[cite Etyemezian et al., 2007 here?]]**), a circular wind-erosion device that measures concentrations of particulate matter <10 μm (PM10) in diameter at different friction velocities (u*) from soil surfaces (Etyemezian et al., 2007; see the Supplemental Material[1]). Concentrations of PM10 can be measured up to 400 mg/m^3, limiting both the size and maximum dust concentrations that can be measured by the PI-SWERL. The friction velocities simulated in this study equate to dust-producing winds, and dust concentrations measured by PI-SWERL were used to calculate dust fluxes (mg/m^2/s) to compare emissions from different landforms. Tests occurred on bare surfaces composed of loose sediment or crusts or on bare spaces between shrubs and grasses. Thus, the PI-SWERL measured dust emission potential of surfaces without vegetation. To assess if soils contained silt and clay that could be entrained as dust, sediments collected at each testing site were analyzed by a laser diffraction method that dispersed samples in water or air to determine percentages of sand, silt, and clay (see the Supplemental Material).

RESULTS

PI-SWERL measurements revealed considerable variation in the dust emission potential of both eolian systems. Active dunes, sand sheets, and interdunes at White Sands generated similarly high dust fluxes (up to 6.9 mg/m^2/s) yet contained no particles <10 µm (Figs. 2A and 2C; Table 1). The playa had the widest range of fluxes (0.00–8.3 mg/m^2/s), with the lowest fluxes on moist or hard surface crusts and high fluxes where loose sand and aggregates were at the surface. Comparison of grain-size distributions of playa samples dispersed in water versus air revealed differences in sand, silt, and clay (Table 1). Dispersion in water yielded higher proportions of silt (>32%) and lower proportions of sand (<80%) compared to dispersion in air (2% and 94%, respectively). These results support observations that playa sediments contain sand-sized aggregates.

In contrast, the Monahans active quartz dunes generated low dust fluxes (up to 0.5 $mg/m^2/s$) yet contained 100% sand (Table 1; Figs. 2B and 2C). Interdunes were typically crusted or had high soil moisture and were low dust emitters; however, higher fluxes occurred on dry crusted interdunes with loose sand at the surface. While vegetation density on stabilized dunes and sand sheets precludes these landforms as major contemporary dust sources, PI-SWERL tests on interspaces between vegetation and on an artificially disturbed sand sheet resulted in much higher dust emission potential (up to 17 $mg/m^2/s$). Vegetated, stabilized dunes and sand sheets contained 0 to >18% silt and clay (Table 1).

Dust emissions increase exponentially with rising friction velocities (Figs. 2A and 2B). At White Sands, winds >18 m/s (u* >> 0.8 m/s) have produced large dust storms (Fig. 2D). Similar wind speeds replicated by the PI-SWERL on dune sand and playa material produced a dust flux up to 4.8 $mg/m^2/s$ (Fig. 2C). These dust fluxes are similar to other highly emissive playa-dune systems, including Owens Lake (Gillette et al., 2004), and other desert landforms (Sweeney et al., 2011). In contrast, the low fluxes from Monahans active dunes were similar to dunes in China that lack silt and clay and were consistent in magnitude to crusted, low-emission playas (Sweeney et al., 2016).

DISCUSSION AND CONCLUSIONS

Our study reveals intra- and extra-landform variability in dust fluxes from eolian systems now and in the future. Most variability can be attributed to the degree of surface crusting or soil moisture (Gillette, 1999). PI-SWERL tests revealed that higher dust emissions occur on surfaces with loose sand or aggregates where saltation bombardment could erode finer-grained playas or where interdunes and aggregates could break apart to

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generate dust. High dust emissions from stabilized sand sheets and dunes were associated with abrasion or saltation and the release of silt and clay likely derived from pedogenesis or dust deposition in those deposits. Wide ranges in dust emissions from sand sheets and playas may be related to fine to very coarse sand sizes, which influence the friction velocity required for entrainment. Surface crusting also reduced dust emissions on playas and interdunes.

Sand abrasion is the likely dominant dust-production process for active dune fields that contain no measurable silt and clay, based on a combination of PI-SWERL and grain-size data. PI-SWERL tests from both active dune fields produced PM10 particles (Fig. 2) and coarse silt sizes (0.015–0.035 mm) by sand abrasion that were not originally present in the dune sand (Fig. 3). At White Sands, the assumption has been that most dust is sourced from the playa (Gunn et al., 2021). A potentially surprising result of this study is the high magnitudes of dust emission from both the abrasion of dune sand and erosion of playa sediments at White Sands, which indicate both landforms are particulate sources during dust storms. In contrast, the Monahans eolian system produced low quantities of dust due to low rates of abrasion in active dunes and vegetative cover, which protects the surface from wind erosion. The results for the Monahans active dunes are consistent with other studies that produced low dust fluxes from quartz sand abrasion (Bullard et al., 2004; Huang et al., 2018; Adams and Soreghan, 2020; Swet et al., 2020).

Jerolmack et al. (2011) studied abrasion at the White Sands dunes and concluded that gypsum grains easily shatter upon impact to produce dust. Our data support this claim (Fig. 3A), where abrasion contributes to the elevated and sustained dust emissions from White Sands dunes. Conversely, the mineralogical maturity and well-rounded nature of the Monahans quartz dune sand are likely due to a history of abrasion that released finer particles (Muhs, 2004). A significant portion of the dust generated from these dunes was also likely deposited and stored in the surrounding vegetated dunes and sand sheets. Dust flux from the active Monahans dunes has likely decreased over time as the rate of particle production with abrasion has decreased with an increase in grain rounding and a decrease in feldspar content (sensu Muhs, 2004). The dust fluxes from quartz dunes, albeit comparatively low, can be appreciable over multidecadal time scales when evaluating global dust loads (Bullard et al., 2004).

Annual magnitudes of dust emissions in metric tons (t; Table S3) from hypothetical 1 km^2 parcels of landforms reveal large differences in average emission potential, with the White Sands dunes emitting 83 t/yr and Lake Lucero emitting 10 t/yr. Maximum emissions occur at higher wind speeds (up to 18 m/s) and on surfaces with weak to limited surface crusting, with 271 t/yr emitted from active dunes and 183 t/yr emitted from Lake Lucero. Mean and maximum fluxes from sand sheets, dunes, and interdunes are similar (Fig. 2C), potentially indicating that abrasion is equally effective in gypsum eolian sand deposits that do not contain silt and clay. Monahans active dunes produce 15–69 t/yr, but high magnitudes of dust emission from this system would require vegetation reduction on sand sheets and dunes. In that case, emissions from sand sheets become the highest at 344 t/yr average, versus 2171 t/yr maximum. Potentially high fluxes from the Monahans system indicate the importance of stored silt and clay in eolian deposits as potential sources of dust.

The key difference between the White Sands and Monahans eolian systems as long-term dust sources is related to differences in sediment supply. The White Sands area

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is a prolific dust source due to seasonal wetting and drying of the playa and recrystallization of gypsum crystals, with winds eroding flat, unvegetated playa sediments that replenish the supply of sand-sized particles to the dunes (Ewing, 2020). This gypsum factory has been operating since at least the early Holocene: Its age and the documented major deflational episodes at 7 ka and 4 ka (Langford, 2003) suggest the White Sands eolian system has been a dust-emission hotspot for thousands of years. Increases in dust emissions from the area may be linked to drought, for example, during the 1930s Dust Bowl (Choun, 1936), as well as during more recent short-term droughts (Fig. 2D). Comparatively, dust from the Monahans eolian system will eventually become exhausted as the sand sheet (0–10 m thick) erodes away on 10^4 to 10^5 time scales. Sand sheets are extensive on the southern High Plains (Fig. 1), and due to increased sediment availability, primarily by agricultural disturbance, they are presently (Lee et al., 2012) significant dust sources in the region. These sand sheets are composed of loamy sands to sandy loams with >10%–15% silt and clay, they have high potential emissivity (Bolles et al., 2019), and they are similar to other sand sheets documented to be dust sources in other countries (Lee et al., 2012, and references therein). Reactivation of vegetated dunes and sand sheets could occur in the southern High Plains with a 10%–15% decrease in precipitation (Muhs and Holliday, 2001). Climate models need to consider the likely increase in dust emissivity from eolian systems during megadrought conditions in the southern Great Plains and elsewhere (Pu and Ginoux, 2017; Bolles et al., 2019).

Landform-based assessments are critical in identification of dust sources and emission potentials (Bullard et al., 2011). Our study is applicable to other drought-sensitive eolian systems where stabilized dunes and sand sheets may become reactivated, or where adjacent playas may bolster emissions, such as Africa (Bhattachan et al., 2013; Bristow and Moller, 2018), Australia (Bullard et al., 2008; Strong et al., 2010), and Asia (Amit et al., 2014). A clear outcome is that multi-magnitude differences in potential atmospheric dust loading can occur from diverse landforms in active and presently stabilized eolian systems. This analysis underscores the possibility **[[or likelihood?]]** that eolian systems, especially those with stored silt and clay, can yield extremely high dust emissions, particularly with projected drying in the midlatitudes for the 21st century (Cook et al., 2020).

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FIGURE CAPTIONS

Figure 1. (A–B) Maps of the Monahans dune field (A) and White Sands dune field (B), USA, with Portable In Situ Wind Erosion Laboratory (PI-SWERL**[[cite Etyemezian et al., 2007 here?]]**) testing sites indicated by white circles (see Table S1 [see footnote 1]). Inset shows locations (black circles) of the White Sands (W) and Monahans (M) dune fields; gray areas indicate the approximate extent of eolian sand deposits. Base maps are from World Imagery (www.arcgis.com).

[[Figure edits needed: Add N and W to at least one lat and long designation each (in each panel) and delete minus signs from longitude values.]]

Figure 2. (A,B) Average dust fluxes of particulate matter <10 µm (PM10) as a function of friction velocity from different dune field environments and source areas for: (A) White Sands and (B) Monahans dune fields (USA). (C) Box plot of dust fluxes at friction velocity $u* = 0.8$ m/s, roughly equivalent to wind speeds of 19 m/s. Boxes represent the 25th to 75th percentiles, with the horizontal line marking the median value; whiskers represent the 10th and 90th percentiles. Dots represent maximum and minimum values. (D) NASA astronaut photograph ISS030-E174652 of a dust storm originating over the White Sands playa and dune field on 28 February 2012 (https://eol.jsc.nasa.gov/Collections/EarthFromSpace/printinfo.pl?PHOTO=ISS030-E-174652). Sustained winds at nearby Holloman Air Force Base (New Mexico) reached 17.8 m/s, with gusts of 21.5 m/s. Black box outlines area of field study in Figure 1B.

[[Figure edits: Put units in parentheses in axis labels in A, B, and C. Specify lat and long for part D.]]

Figure 3. Dune sand and abrasion products produced during Portable In Situ Wind Erosion Laboratory (PI-SWERL**[[cite Etyemezian et al., 2007 here?]]**) tests. (A) Silt-sized gypsum produced from abrasion of sand (inset photo) from the White Sands (New Mexico, USA) dunes, location WS16 **[[Do you mean site W16-18 from Figure 1?]]**. (B) Silt-sized quartz produced by abrasion of sand (inset photo) from Monahans dunes, location M1 (see Figure 1).

[1]Supplemental Material. **[[Please provide a brief caption here.]]**. Please visit https://doi.org/10.1130/XXXXX to access the supplemental material, and contact editing@geosociety.org with any questions.

TABLE 1. DUST EMISSION FLUXES AND GRAIN-SIZE DATA FROM DUNE FIELDS IN NEW MEXICO AND TEXAS, USA

	Dust emission ($mg/m^2/s$)						Grain size#			
Landform	*n*	Geomean* *u* = 0.4 m/s	CI low†	CI high§	Maximum *u* = 0.9 m/s	Minimum *u* = 0.4 m/s	% sand (st. dev.)	% silt (st. dev.)	% clay (st. dev.)	% PM10** (st. dev.)
White Sands										
Active dune	15	0.038	0.037	0.039	6.20	0.01	99.6 (0.2)	0.4 (0.2)	0	0
Sand sheet	13	0.038	0.036	0.039	6.91	0.01	99.6 (0.2)	0.3 (0.2)	0	0
Interdune	14	0.018	0.017	0.019	5.16	0.003	99.8 (0)	0.2 (0)	0	0
Playa (water)	43	0.007	0.007	0.008	8.29	0.000	80.8 (36.6)	15.1 (26.6)	10.5 (12.9)	32.0 (29.2)
Playa (air)							93.7 (9.7)	5.9 (8.6)	0.4 (1.2)	2.2 (5.3)
Monahans										
Active dune	28	0.012	0.011	0.012	0.52	0.003	100 (0)	0	0	0
Vegetated dune	9	0.070	0.069	0.070	2.14	0.04	96.1 (1.9)	3.5 (1.6)	0.4 (0.3)	1.3 (0.8)
Sand sheet	16	0.224	0.217	0.230	17.68	0.01	86.1 (5.1)	12.2 (4.2)	1.7 (0.9)	3.9 (1.8)
Interdune	16	0.006	0.005	0.006	1.42	0.001	93.0 (17.0)	5.9 (13.8)	1.1 (3.2)	2.5 (7.2)

*Most common friction velocity (*u*) above threshold for entrainment (Pedersen et al., 2015 **[[Not in the Reference list.]]**).
†95% confidence interval (CI) below the mean.
§95% confidence interval (CI) above the mean.
#All White Sands (New Mexico) grain sizes were determined by dispersion in air; all Monahans (Texas) samples were dispersed in water. White Sands playa material was dispersed in water for comparison. St. dev.—standard deviation.
**PM10—particulate matter <10 μm.