Effectiveness of an array of porous fences to reduce sand flux: Oceano Dunes, Oceano CA

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ABSTRACT

Arrays of porous fences, ≈12 ha in 2014 and ≈15 ha in 2015, were constructed in the Oceano Dunes State Vehicular Recreation Area to evaluate their effectiveness to reduce sand flux and affect local PM10 dust concentrations. The 1.22 m high, ≈244 m long, ≈50% porous fences were placed 10 fence heights apart in 2014 and 7 in 2015. Measurements of sand flux through the arrays indicated that it diminished exponentially with increasing distance, reaching equilibrium at ≈93 fence heights for the 10 h spacing and ≈27 fence heights for the 7 h spacing. Fences spaced 7 h apart reduced sand flux for the entire area by 78%, and 86% for the area ≈27 h. Fences spaced at 10 h reduced sand flux for the entire area by 40%, and 56% for the area ≈93 h. PM10 monitoring upwind and downwind of the array and in the absence of the array in 2015, indicated that the downwind PM10 concentration was less than the upwind for the fence array, whereas in the absence of fences PM10 increased in the downwind direction over the same fetch distance, suggesting the presence of the fences was reducing the flux of PM10 from within the fence array.

1. Introduction

The Oceano Dunes, part of a quaternary age coastal dune complex (Orme and Tchakerian, 1986) in California (Fig. 1), contains the Oceano Dunes State Vehicular Recreation Area (ODSVRA) California State Park consisting of ≈500 ha of dune environment that allows off-road recreational vehicle activity as well as ≈280 ha of dune preserve that only allows access by pedestrians. Under conditions of elevated wind speed, typically >5 m s⁻¹ with a dominant westerly component as measured 10 m above ground level (AGL), the threshold for sand transport is exceeded and once this occurs it is accompanied by dust emissions (Gillies and Etyemezian, 2014). For periods of wind erosion within the dune system that last for >6 h, air quality measurements made by the San Luis Obispo County Air Pollution Control District (SLOCAPCD) downwind of the eastern boundary of the park have been observed to exceed the 24 h mean standard for the mass concentration of particulate matter ≤10 μm aerodynamic diameter (i.e., PM10) for both US EPA and California State air quality regulations (i.e., 150 μg m⁻³ US EPA, 50 μg m⁻³ California Air Resource Board). As part of an on-going effort to reduce PM10 dust emissions that contribute to the violation of the standards and that are associated with the saltating sand in the dune areas, control measures are being evaluated.

Fences of various construction materials and design are used to control the location and rate of erosion and deposition of sand and snow. By extension, the control of saltation of sand-sized particles moving across sediments containing silt and clay-sized particles will also affect the dust emission process driven by the ballistic impact of these grains on to the surface (Gomes et al., 1990; Shao, 2001; Shao et al., 1993). In 2014, 20 parallel rows of sand fences 1.22 m high and ≈244 m long separated by a distance of 10 fence heights (≈12.2 m) and oriented perpendicular to the expected dominant sand transporting wind direction (WNW) encompassing ≈12 ha were established and left in place for three months. In 2015, 35 parallel rows of the same type of fence, with the same orientation having a separation distance of seven fence heights (≈8.5 m) were emplaced in a different area of the ODSVRA encompassing ≈15 ha and left in place for four months. We report here on the effectiveness of these arrays of sand fences to modulate sand flux over the area they covered and how the array in 2015 influenced PM10 concentration from the...
upwind to downwind extent of the array. The expectation is that controlling sand flux will also reduce the flux of PM10 that contributes to the observed levels that breach the air quality standards. There is a rich scientific literature describing the effect that two dimensional barriers, solid and porous, have on airflow in front and in the lee of these structures. Sand fences deployed for their intended purpose of modifying wind erosion processes are always porous. Li and Sherman (2015) trace the formal research for sand fences to Bates (1911), with more thorough scientific-based investigations occurring in the 1930s. Most of this research, even up to the present time, has focused on single lengths of fence placed perpendicular to the flow (e.g., Lee and Kim, 1999; Dong et al., 2011; Ping et al., 2013; Tsukahara et al., 2012; Zhang et al., 2015). Much less research has been published on airflow over multiple barriers (e.g., Woodruff and Zingg, 1955; Iqbal et al., 1977; McAneney and Judd, 1991; Wilson and Yee, 2003; Bitog et al., 2009). Li and Sherman (2015) note in their extensive review of the literature related to sand fences that there have been few controlled fence experiments with sand transport. Li and Sherman (2015) present a thorough review of the aerodynamics and morphodynamics of sand fences. Here we provide a brief review of the key aspects of what is known of flow and sand transport as affected by fences with the reader referred to Li and Sherman (2015) for detailed information.

The aerodynamics and morphodynamics of a fence depend on the geometry of the fence design, with the elements of height, length, width, porosity, opening size/distribution/geometry, and orientation relative to the wind being most important. Fence porosity (\(\varepsilon\)), the ratio of a fence's open area to its total area is considered the most important single parameter controlling its performance and usually reported as a percentage of open area (Bean et al., 1975). Permeability is a related characteristic that relates the velocity, \(u\), of the air through the material (under the action of a pressure gradient) to the pressure gradient across the material as defined by Darcy's Eq:

\[
u = \left(\frac{K}{\mu}\right) \frac{\partial p}{\partial x} \tag{1}
\]

where \(K\) is the permeability with units of length squared, \(\mu\) is the dynamic viscosity of the fluid, \(p\) the pressure and \(x\) the direction of flow. \(K\) represents the ability of the material to transmit fluid through itself and depends on the material porosity (\(\varepsilon\)) and the pore's characteristics.

The flow behind a single porous fence can be generalized as follows: a new boundary layer is created at the edge of the fence with large eddies developing just downwind and that boundary layer returning to equilibrium a certain distance in the lee of the fence generally at distances \(\gg 10 h\), where \(h\) is fence height (Fig. 2). Immediately behind the fence is the bleeding flow zone where individual jets are formed when the air passes through the fence (Wilson et al., 1990), followed by the recirculating or standing eddy zone (Plate, 1971) wherein flow at the surface is towards the fence (opposite the above-fence flow). The blending zones are found where the flow from the middle layer blends with the region where the flow begins to establish the new boundary layer and between the middle layer and the outer layer (Fig. 2).

Woodruff and Zingg (1955) provide a comparative analyses of airflow patterns about a multiple porous fence array (four fences, spaced at 15 h) for both a field setting and a scaled wind-tunnel test. They observed
that three or four successive barriers are insufficient to reach a maximal cumulative effect on the air flow. They also noted that successive fences cause the zone of maximum near-surface wind speed reduction to occur nearer to the second and third fences than the first. Their wind speed measurements also indicated that the maximum velocity fluctuations between two successive fences occurred at 6 h, with the greatest disturbance of the air flow at 0.125 h AGL at 2 h and 6 h behind the first barrier.

McAneney and Judd (1991) present a schematic of the wind field behind a fence deep in an array (Fig. 3) on a relatively flat surface. They observed from field measurements that most of the boundary-layer adjustment to the increased surface drag created by the presence of the fences occurred in a distance of eight fence rows, with an equilibrium condition thereafter. Their definition of equilibrium is that the flow between successive windbreaks is dynamically similar and that inputs of turbulent energy are approximately balanced by losses between adjacent fences. Wilson and Yee (2003) used McAneney and Judd (1991) results to test the performance of simple Reynolds-averaged Navier-Stokes (RANS) models to reproduce the turbulent kinetic energy (TKE) in a windbreak network. They found that all closure methods they considered gave mediocre predictions and suggest this is due to the inability of the models to effectively treat the parameterizing of the flow-fence interaction not only for the TKE and dissipation rate equations, but also the momentum equations.

Sand fences are deployed to reduce wind speed over erodible surfaces, which should lower the probability of entrainment and reduce transport rates of sand in their lee. The degree of wind speed reduction in the stream-wise direction defines their shelter distance (d), which can be referenced to the distance downwind to reach a specified proportion of the undisturbed wind speed (e.g., 50%, 100% or the wind speed (or shear stress) required to achieve the threshold for transport). For fences that have holes to create porosity (as opposed to vertical slats) shelter distance is maximized for fence porosities between $\varepsilon = 0.30-0.40$ (Cornelis and Gabriels, 2005; Dong et al., 2006; Jensen, 1954). Bitog et al. (2009), report from wind tunnel testing that $\varepsilon = 0.2$ created the greatest decrease in wind speed from the surface to the height of the fence. For slat-type fences Dong et al. (2011) found the maximum wind speed reduction occurred at $\varepsilon = 0.1$.

Porosity and permeability of the fence also affect the transfer of sand through the fence. Fences of the same porosity can be constructed with holes of different size and shape (e.g., square, rectangular, round). Manohar and Bruun (1970) carried out wind tunnel tests that demonstrated for the fences they tested, the smallest slat gap had the greatest trapping efficiency and that trapping efficiency decreases as gap size increases. Field studies by Savage (1963) and Savage and Woodhouse (1968) also observed that fabric fences with smaller openings trapped more sand than slat fences with the same porosity and height. To prevent blocking through a pore or between slats, Hotta et al. (1987) suggest that the opening size needs to be $\geq 10$ times the diameter of the sand. Zhang et al. (2015) closely examined the effect that a porous fence had on the speed and trajectory of sand particles after they had passed through the pores and reported that particle speed was slowed between 50% and 36% for particles of diameter 250 μm and 100 μm, respectively. They also observed that this reduction in particle speed scaled as a function of grain diameter with smaller particles decreasing their speed to greater extent than larger ones. Thus, the fence effectively reduces the impact velocity of sand grains in the region in its lee. This suggests that further manipulation of fence permeability characteristics affecting the passage of saltating sand particles could be used to improve fence performance.

Information on how the flux of sand is affected as it encounters multiple fences of various separation distances is very limited in the literature. Gill et al. (2003) deployed a staggered array of 22, 76 m long sand fence panels at Owens Lake, CA, spaced 55 fence heights apart and reported that sand transport was 88% lower than the flux upwind and downwind of the array and for measurements of flux made adjacent to the array in an area without sand fences. White et al. (2003) carried out a wind tunnel experiment to evaluate how sand fences $\varepsilon = 0.50$ could affect sand transport. They measured the ratio of wind shear velocity to threshold wind shear velocity as a function of downwind distance for multiple fences of varying spacing and developed sand transport-control relationships site-specific to Owens Lake, CA. Their study did not involve sand interacting with model fences.

Designing a wind tunnel study that involves multiple model fences and saltating sand would be exceedingly difficult as there will be constraints on scaling the size of the model fences to the size of the sand grains and the length scales of the saltation process as well as the diameter of the sand with respect to the size of the pore openings in the model fence. A further complication is that it has recently been suggested that saltation in wind tunnels is altered in its length scale characteristics compared to unconstrained wind driven saltation (Sherman and Farrell, 2008; Li and McKenna Neuman, 2012; Martin and Kok, 2017). Available saltation models such as COMSALT (Kok and Renno, 2009) are not...
configured to account for the presence of macro-scale roughness elements, which limits their use to evaluate how an array of fences will modulate the saltation process.

Testing at the full scale in the atmospheric boundary layer can be difficult due to the vagaries of weather, wind conditions, and the native spatial (Gares et al., 1996; Jackson et al., 2006) and temporal variability (Lee, 1987; Stout and Zobeck, 1997; Bauer et al., 1998) of sand transport, which can introduce high variability in measurements of mean quantities (e.g., saltation flux). Nevertheless, it offers the best opportunity to observe the interaction of saltating sand with porous fences in the absence of boundary-layer and scaling effects that are present in wind tunnel testing.

2. Material and methods

2.1. Sand fence array design

As we were unaware at the planning stage of any theoretical or empirical relationships to guide the engineering of a multiple sand fence array (e.g., White et al., 2003) to meet a design objective for sand flux reduction, the following rationale was used. For construction purposes and cost considerations the choice of fencing material was a flexible plastic mesh 1.22 high (h), with ovoid holes ≈8.2 cm by ≈3.7 cm holes and 209 holes per 1 m² of mesh, ε ≈ 0.56 (Fig. 4). In order to evaluate how this fencing could influence sand transport we made use of the relationship of Bradley and Mulhearn (1983) that shows the reduction in shear velocity, *u* (Prandtl, 1935), in the lee of a porous (ε = 0.50) fence can be evaluated by:

\[
\frac{u_{\text{lee}}}{u^*} = 0.201 \ln(ND) + 0.429
\]

where *u* is the shear velocity at positions downwind of the fence, *u* is the shear velocity without the fence present, and ND is normalized distance (distance downwind of fence/fence height). For a threshold shear velocity, *u*t, we assumed the typical value for fine sand of 0.3 m s⁻¹ (*u*_10m ≈ 8 m s⁻¹). For a 1.22 m high sand fence when the regional *u* = 0.3 m s⁻¹, the distance downwind of the fence where sand motion commences will be at ≈15 h. This distance decreases as regional *u* increases. The effectiveness of fences to reduce sand flux for fences placed at 6 h, 8 h, 10 h, and 15 h can be evaluated based on how far past the fence *u*_{lee} reaches *u*t and the mean shear stress in the zone that extends to the point of full recovery (i.e., *u*_{lee}/*u* = 1). Based on the fraction of surface that would be below threshold at a regional *u* = 0.4 m s⁻¹ (*u*_10m ≈ 10 m s⁻¹), and hence provide a 50% reduction in sand transport between two consecutive fences the spacing of 10 h was chosen as the fence spacing design criteria for 2014.

The fence arrays were constructed by ODSVRA personnel. To anchor the fences 2.4 m long, 0.13 diameter wooden posts were driven into the sand approximately 12.2 m apart. A screen made of 3.175 mm diameter wire interlaced to make holes 0.203 m by 0.152 m, with 36 holes per 1 m² was strung continuously between the wooden posts. The plastic fence material was subsequently affixed to both sides of the wire mesh, offset slightly to achieve ε ≈ 0.5.

In 2014, 20 fence rows ≈244 m long and spaced ≈10 h (12.2 m) apart were deployed in a roughly rectangular shape within the ODSVRA (Fig. 5) creating an area of ≈12 ha defined by the perimeter. For 2015, using the same fencing method and materials, 35 fence rows were established in a different location creating an area of ≈15 ha (Fig. 5). Spacing between the fences was changed to ≈7 h to evaluate how this could further affect the sand flux reduction characteristics of the array. The irregular shape was due to the topography and the need to not...
Fig. 5. The position of the sand fence array 2014 in the ODSVRA (orange square, large panel) and 2015 array (gray polygon, large panel). Inset panel shows details of the 2015 sand fence array with fences demarcated with parallel lines, the transects of BSNEs as red lines and ID labels A, B, and C and the position of the E-BAMS: E1, E2, E3, E4, and the anemometer/wind vane measurement locations, T1 and T2. The blue line marks the park boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
impinge upon a key travel route for vehicles operating within the ODSVRA, especially emergency access vehicles. Due to the constraints of operating large machinery within the undulating dune topography (e.g., steep slip faces and sides), some of the fence rows (in both years) were discontinuous. In 2014, 2015, the fraction of area where fences could not be emplaced due to terrain constraints represented ≈10% and ≈20%, respectively, of the total area defined by the perimeter of the arrays.

2.2. Instrumentation

In 2014, two types of sand traps were used to measure sand flux exterior and interior to the array. Thirty-six Big Spring #8 (BSNE) traps (Fryrear, 1986) and 12 Cox Sand Catchers (CSC) (Gillies et al., 2015) were placed in the fence array as illustrated in Fig. 6. In 2015, 54 BSNE style traps were placed into the array as illustrated in Fig. 6. For both years of measurement, the bottom of the trap orifice was set at 0.15 m.

The placement of the traps in the array in 2014 created five linear transects through the array. The array of samplers in the north and south positions were ≈40 m from the edge of the array with a separation of ≈40 m between the three instrument array transects interior to the north and south lines. A BSNE and CSC trap were placed 1.22 m in front of the western-most (upwind) sand fence for each sampling transect. In between successive fences one to three traps were placed at 1 h (≈1.22 m), 5 h (6.10 m), and 9 h (10.98 m). The middle transect had the highest number of traps (19) and the north, south and middle transects had traps emplaced beyond the last fence.

CSC style traps were not used in 2015 as they proved to be too difficult to maintain a consistent orifice height under the sand flux conditions encountered, especially upwind of the array. A different pattern of traps was used in 2015. Three linear transects one with 18 and two with 20 BSNE traps, placed within eight consecutive fences were established within the array and designated with the letters A, B, and C. Transect A was the furthest north and C the furthest south (Figs. 5 and 6). Transect A consisted of two BSNE traps ≈1.22 m upwind of the first fence in the array, separated in the north-south direction by ≈2 m, followed by 16 BSNEs placed perpendicular to the fence alignment with one or three BSNEs placed between consecutive fences. Transect B consisted of two BSNE traps ≈1.22 m upwind of the first fence in the array, separated in the north-south direction by ≈2 m, followed by 18 BSNEs placed perpendicular to the fence alignment with one or three BSNEs placed between consecutive fences. Transect C was established at the 13th fence row from the leading western fence, to provide characterization of sand flux patterns deep into the array. Two BSNE traps were placed ≈1.22 m west of the 13th fence, separated in the north-south direction by ≈2 m, followed by 18 BSNEs placed perpendicular to the fence alignment with one or three BSNEs placed between consecutive fences. For 2015, the general pattern for positioning the BSNEs between two consecutive fences was to place them at 1 h (≈1.22 m), 3 h (≈3.66 m), and 6 h (≈7.32 m) measured from the western fence. In the case where only one BSNE was placed between consecutive fences it was located at the 6 h position. Typically sand transport events occur at the dunes between 10 a.m. and 6 p.m. The sand in the traps was emptied into labelled Ziploc® bags the morning after a transport event and retained for weighing. Samples were dried and weighed to 0.01 g precision.

In 2015 the effect of the sand fence array to modulate the associated dust emissions was examined by placing PM10 monitors (E-BAM, Met One Instruments, Inc., Grants Pass OR) at four locations in the vicinity of the sand fence array (Fig. 5) for May through July. Two samplers were located at the fence array. The first (E1) was located just upwind of the leading (western) edge of the array and the second (E2) at the trailing (eastern) edge of the array and aligned with each other along the line perpendicular to the fence direction, separated by a distance of ≈375 m. A wind vane and anemometer downwind of the array was also positioned with the E-BAM located at the downwind edge of the array from May to July 31, 2015 (T1, Fig. 5). The second pair of PM10 monitors (E3 and E4) was located approximately ≈490 m to the south separated by ≈300 m aligned along the same azimuth, but with only open sand between them (Fig. 5). A wind vane and anemometer were positioned with the E-BAM located furthest to the east from June 9 to July 31, 2015 (T2, Fig. 5).

3. Results

3.1. Sand transport event conditions

In 2014 between 04-09-2014 and 06-30-2014, 29 separate sand transport events were sampled with the sand traps. Of note is that for the dates 4-18-2014, 4-19-2014, 4-21-2014, 6-21-2014, and 6-22-2014, the mass of sand collected in the traps was low (total trap mass [5 BSNE traps placed between successive fences one to three BSNEs placed between consecutive fences. Transect B consisted of two BSNE traps ≈1.22 m upwind of the first fence in the array, separated in the north-south direction by ≈2 m, followed by 18 BSNEs placed perpendicular to the fence alignment with one or three BSNEs placed between consecutive fences. Transect C was established at the 13th fence row from the leading western fence, to provide characterization of sand flux patterns deep into the array. Two BSNE traps were placed ≈1.22 m west of the 13th fence, separated in the north-south direction by ≈2 m, followed by 18 BSNEs placed perpendicular to the fence alignment with one or three BSNEs placed between consecutive fences. For 2015, the general pattern for positioning the BSNEs between two consecutive fences was to place them at 1 h (≈1.22 m), 3 h (≈3.66 m), and 6 h (≈7.32 m) measured from the western fence. In the case where only one BSNE was placed between consecutive fences it was located at the 6 h position. Typically sand transport events occur at the dunes between 10 a.m. and 6 p.m. The sand in the traps was emptied into labelled Ziploc® bags the morning after a transport event and retained for weighing. Samples were dried and weighed to 0.01 g precision.

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combined] upwind and exterior to the fences <20 g). In 2015 between 04-14-2015 and 06-25-2015, 22 separate sand transport events were sampled with the sand traps.

With the inclusion of the PM$_{10}$ monitoring in 2015 a record of the wind speed and direction at the fence array was obtained for the days represented by sand trap samples. In 2015, for hourly mean wind speed and direction at 10 m for mean speed $\geq 5$ m s$^{-1}$ (assumed threshold for sand transport/dust emissions) the wind direction range was 282.5°–312.5°, which was −9.5° to 20.5° from perpendicular to the orientation of the fence array. The percentage occurrence of hourly mean wind direction for mean hourly wind speed $\geq 5$ m s$^{-1}$ is shown in Fig. 7. The winds were more frequently shifted to the north of the perpendicular for ND 04-14, 04-19, 04-21-14, and 06-22-14) were not included in the calculation of the mean NSF values.

In 2015 the mean NSF values for the zones defined by ND 6–20 (high variability of NSF), and ND $\geq$ 27 (low variability of NSF) for the three transects are presented in Table 1. In 2015, in the zone of higher flux variability and where NSF decreases exponentially with increasing ND (i.e., transects A and B) the mean NSF was lower by approximately one half compared to 2014, although with a very high standard deviation ($\pm 0.06$). For the zone of lower flux variability in 2015, the mean NSF was lower by a factor of 3.4 (just BSNE data) compared to 2014.

3.3. Mean sand flux in the array

For both years the sand flux reduction is characterized by two zones: a highly variable zone that extends to a certain ND followed by a zone of lower variability through to the end of the array. For 2014, the zone of high flux variability was between ND 6–93 and the zone of decreased flux variability was ND $\geq$ 93. The mean NSF values and their respective standard deviation values are provided in Table 1. The events with very low sand catches with very low sand catches (04-18-14, 04-19-14, 04-21-14, 06-21-14, and 06-22-14) were not included in the calculation of the mean NSF.

3.4. PM$_{10}$ concentration changes at the array and exterior to the array

To examine how the presence of the fence array may be affecting the airborne concentration of PM$_{10}$ the hourly mean data from the E-BAMs were filtered by wind speed ($\geq 3$ m s$^{-1}$) and wind directions approaching the array through 22.5° either side of normal (i.e., 270°–315°) using the meteorological data collected at position T1 for E1 and E2 (Fig. 5), and for E3 and E4 for dates prior to 06-09-2015, and at position T2 from 07-09-2015 through to 07-31-2015. The relationship between mean PM$_{10}$ and mean hourly wind speed for 1 m s$^{-1}$ bins from 3.5 to 11.5 m s$^{-1}$ are plotted for May, June, and July 2015 in Fig. 10. Fig. 10 shows that PM$_{10}$ responds to wind speed in a non-linear fashion and the threshold wind speed for dust emission lies between 5 m s$^{-1}$ and 6 m s$^{-1}$. Along with the mean PM$_{10}$ concentration for each 1 m s$^{-1}$ wind speed bin, the best fit power function equation is shown for the wind speed bins $>5.5$ m s$^{-1}$.

During May 2015, a decrease in PM$_{10}$ concentration was observed between E1 and E2 when the winds were above threshold with the difference dependent on wind speed. For the wind speed bin 5.5 m s$^{-1}$ E2 was 26% lower than E1. That difference decreased to 23% for the 10.5 m s$^{-1}$ bin, based on the best fit regression relationships (Fig. 10). For June, E2 was lower than E1 for equivalent wind speed bins for the mean hourly PM$_{10}$ data pairs, but the regression-derived data values suggest equivalence. For July there appears to be no appreciable difference in PM$_{10}$ between E1 and E2.

For the pair of E-BAM samplers E3 and E4, which are south of the array and have no fences between them the differences in the mean hourly PM$_{10}$ as a function of mean hourly wind speed for May, June, and July are also shown in Fig. 10. For May, this pair of samplers shows higher PM$_{10}$ values for the sampler further to the east with the E4 sampler $\approx 26\%$ higher than the E3 sampler for the 5.5 m s$^{-1}$ mean hourly wind speed bin increasing to 45% higher for the 10.5 m s$^{-1}$ wind speed bin. For June and July, for equivalent hourly wind speed bins, E4 is higher than E3, but the difference is $\approx 5\%$ at lower wind speeds increasing to $\approx 13\%$ at the highest wind speed bin of 10.5 m s$^{-1}$.

4. Discussion

4.1. Sand fence effectiveness to reduce sand flux

The sand fence arrays constructed in the ODSVRA represent the largest test areas to date for evaluating the effectiveness of multi-fence arrays to modulate the flux of saltating sand and the associated dust emissions in a coastal dune environment. The mean NSF weighted by the relative areas of the zones of high flux variability (ND < 93, NSF = 0.86) and lower variability (ND > 93, NSF = 0.44) gave a sand flux reduction for 2014, of NSF = 0.60 ($\pm 0.20$), which is 10% higher than the design...
target of 0.5, although the target was exceeded for 62% of the area. In 2015, the sand fence array was not rectangular and contained areas where fences could not be placed due to topographical constraints. Based on its irregular shape and the places where fences could not be placed, a better approximation of the sand flux reduction by the entire array needs to take this into account. The mean NSF weighted by the relative areas of the zones of high flux variability (ND ≤ 20, NSF = 0.49), lower variability (ND ≥ 27, NSF = 0.12), and for the gap areas without continuous fences (NSF = 0.62), gives an overall effectiveness of sand flux reduction for 2015, of NSF = 0.27 (±0.22). The value of NSF for the gap areas was calculated by dividing the mean mass of the two traps to the west of the fence marking the beginning of transect C by the mean of the four mass measurements upwind of transects A and B for each of the 23 events and then taking the mean of these 23 values. By moving the distance between consecutive sand fences from 10 h to 7 h, the effectiveness of the sand fence array to reduce sand flux was increased by a factor of 2.2.

As noted by previous researchers (e.g., Gares et al., 1996; Jackson et al., 2006; Stout and Zobeck, 1997) the saltation process, even on relatively simple (i.e., flat) sand surfaces possesses significant variability across space and through time. Gares et al. (1996) showed span-wise transport variability on the order of 25% over 15-min intervals. Jackson et al. (2006) found transport variability commonly exceeded 150% over a span-wise distance of 5 m. It is this inherent variability in wind-driven sediment transport, and the effect of the fences to enhance turbulence (Wilson and Yee, 2003) and increase maximum velocity fluctuations (Woodruff and Zingg, 1955) as the flow encounters the fences that gives rise to the high levels of variability of sand flux reported here.

The 2015 NSF data, binned by their relative position between consecutive fences (i.e., 1 h, 3 h, and 6 h), show that the 3 h position has a discernible change in the distribution of NSF magnitude compared to the distributions for the traps placed at 1 h and 6 h (Fig. 11). The 3 h position shows a distribution of NSF shifted towards higher values and is also the location where the highest NSF values are observed regardless of which sequential fences are examined. The higher sand flux at 3 h coincides with the transition at the surface from a zone of low turbulence to higher turbulence in McAneney and Judd, (1991) equilibrium flow model (Fig. 3). Higher flux between fences is not associated with the 6 h position, where Woodruff and Zingg (1955) observed a zone of maximum velocity fluctuations between successive fences.

The variability in sand flux is further enhanced by wind direction changes that occur during a transport event. These directional shifts in wind alters the surface shear across the surface as the flow interacts with the fences at oblique angles. The patterns of sand flux reduction as a function of ND and the decrease in its variability with increasing ND presented here provide, for the first time, a clearer picture of the effect of multiple porous barriers on sand transport and demonstrate a relation with the flow conditions as described by McAneney and Judd (1991).

The mean NSF results can be compared with the predicted effectiveness of multiple sand fences to reduce sand transport as presented by White et al. (2003). Based on their derived sand transport control equation for multiple fences:

\[
\text{Sand Transport Control(\%)} = A \left( \frac{L}{h} \right)^2 + B \left( \frac{L}{h} \right) + 1
\]

where L is distance between fences, and A and B are functions of the ratio of the shear velocity to the threshold shear velocity (i.e., $u_*/u_{*t}$), and with the wind shear velocity a factor of 1.5 above threshold, for the 10 h array of 2014 and 7 h array for 2015, White et al. (2003) wind tunnel-derived model predicts NSF = 0.1 and NSF = 0.07, respectively. For the 10 h and 7 h arrays the estimated NSF in the zone where the sand flux was in equilibrium were both higher than the model predicted values (i.e., 0.44 (±0.18) and 0.12 (±0.32)), which suggest the White et al. (2003) model over-predicted effectiveness as a function of fence separation distance for these fence arrays. White et al. (2003) based their model on predicted downwind changes in shear stress behind fences and did not actually measure sand flux as part of their experiments, which may in part explain some of the discrepancy between the field measurements and the wind tunnel model. White et al., (2003) model was also developed for winds perpendicular to the array, whereas this was not the case for our field site. Another distinct difference between the wind tunnel and the field

Fig. 8. Relationship between mean Normalized Sand Flux (all events with total BSNE sand catch >20 g and all traps at the same ND position) and Normalized Distance for 2014. Error bars represent the standard deviation of the mean NSF value.
Fig. 9. Relationship between mean Normalized Sand Flux (all events) and all BSNE traps at the same ND position between fences for transects A (white triangle) and B (black diamond) (top panel) and separately for transect C (bottom panel) for 2015. Error bars represent the standard deviation of the mean NSF value. For Transect A (top panel), the data for ND = 6 were not included in the least squares regression. For transect C (bottom panel) numbers in parentheses on the x-axis represent ND as measured from the first fence in the array.

Table 1
NSF characteristics for 2014 and 2015.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Mean NSF</th>
<th>Std. Dev NSF</th>
<th>Mean NSF</th>
<th>Std. Dev NSF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ND &lt; 93</td>
<td>ND &lt; 93</td>
<td>ND &gt; 93</td>
<td>ND &gt; 93</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A, B, C combined [BSNEa]</td>
<td>0.86</td>
<td>0.93</td>
<td>0.44</td>
<td>0.18</td>
</tr>
<tr>
<td>A, B, C combined [CSCb]</td>
<td>0.73</td>
<td>0.49</td>
<td>0.56</td>
<td>0.34</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A, B, C combined [CSCc]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A, B</td>
<td>0.76</td>
<td>2.84</td>
<td>0.09</td>
<td>0.21</td>
</tr>
<tr>
<td>B</td>
<td>0.20</td>
<td>0.35</td>
<td>0.17</td>
<td>0.44</td>
</tr>
<tr>
<td>C</td>
<td>0.09</td>
<td>0.09</td>
<td>0.12</td>
<td>0.33</td>
</tr>
<tr>
<td>A, B, C combined</td>
<td>0.48</td>
<td>2.06</td>
<td>0.13</td>
<td>0.36</td>
</tr>
<tr>
<td>A, B, C combinedc</td>
<td>0.12</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Data are from the BSNE-style traps.
b Data are from the CSC-style traps.
c All C data used for the ND > 20 case.
The situation is the topographic relief associated with the dunes may be playing a role not accounted for in the model. White et al. (2003) model is based on the developing internal boundary layer that contains the fences on a flat surface, whereas on the dunes the fences are placed where there is considerable topographic relief, which may be creating along with the sand fences, multiple internal boundary layer conditions that the model does not take into account.

The results of Gill et al. (2003) are more difficult to reconcile with the results of this study. Gill et al. (2003) report, for fences 1.22 m and 1.6 m high, spaced ND = 55 apart, a reduction in sand transport that is 88% lower (i.e., NSF = 0.12) within the sand fences than sand transport exterior to their array. According to the White et al. (2003) model, the expectation would be a 60% reduction. Based on the results presented here and observations during transport events at the ODSVRA, it is difficult to imagine that a between fence spacing of ND = 55 would have had any measureable effect on sand flux under the conditions present at the ODSVRA, except within close proximity to a fence. The test site of Gill et al. (2003), which was on the Owens (dry) Lake CA, was described as being a thin sand sheet overlying a crusted playa surface, which may account in part for the difference as compared to the ODSVRA conditions. The sand supply at Owens Lake was much more restricted than the essentially limitless supply at the ODSVRA. Gill et al. (2003) note that there are periods when the surface at Owens Lake was affected by crust development, which would also potentially interfere with sand transport processes and the magnitude of the flux for different wind conditions.
4.2. Changes in sand flux as it enters the fence array

The decrease in sand flux as it encounters a step change in roughness has been reported by Gillies et al. (2006, 2015) and Gillies and Lancaster (2013) for field-scale studies using arrays of large (>0.3 m high) spatially distributed roughness elements. These papers reported that NSF decreases exponentially with increasing ND, reaching an equilibrium value some distance into the array. The rate of change of the reduction in NSF with ND, as observed in those studies, was a function of the roughness density, \( \lambda \) (\( \lambda = \text{(element frontal area \times \#elements)} / \text{surface area occupied by the elements} \)) of the array. In this experiment the 2-dimesional fences also exhibit an exponential reduction in NSF as a function of ND. Based on the results of McAneney and Judd (1991) it could be expected that the sand flux would approach equilibrium conditions at eight fence heights (ND \( \approx 48 \) for their experiment), as this is the distance at which they claim the flow conditions will be in equilibrium with the fences. The measurements from this study suggest that a greater distance is required for the sand flux to come into equilibrium for the fences spaced at 10 h (ND \( \approx 97 \)), and a lesser distance for the fences spaced at 7 h (ND \( \approx 27 \)).

For fences approximately perpendicular to the direction of the sand bearing winds, the rate of change of sand flux appears to be controlled by the inter-fence spacing. A 30% decrease in the spacing distance between fences resulted in NSF decreasing by a factor \( \approx 2.2 \), and the distance to reach equilibrium NSF decreased by a factor of \( \approx 4.7 \). In terms of horizontal distance the change is from \( \approx 114 \) m to \( \approx 31 \) m. The two-dimensional fences cannot be characterized by \( \lambda \), but comparing the two roughness types in terms of an equal NSF of 0.22 demonstrates their relative effects on the rate of change of sand flux with distance. To achieve NSF = 0.22 would require \( \lambda \approx 0.031 \) for an array of 0.3 m high roughness elements (Gillies et al., 2015) with the distance to reach an equilibrium flux of \( \approx 51 \) m (ND \( \approx 170 \)). At least for this level of control effectiveness it appears that the 2-dimensional fences modulate the sand flux at a faster rate than the 3-dimensional roughness array.

The decrease in the distance to reach equilibrium flux for the fences may be due to several factors. Plausible mechanisms that could explain this result include the interaction of the sand with the porous fence and an effect related to element height. A porous barrier, as described by Zhang et al., (2015), effectively slows the sand as it passes through by up to 50%, thus reducing its kinetic energy as well. For the solid roughness elements used by Gillies et al. (2015) some sand will impact the element and rebound thus offering a reduction in sand speed as well, but sand will also be swept around the edges of the solid elements where local shear is increased (McKenna Neuman and Bédard, 2015), which may slow the loss of kinetic energy of the system with downwind distance compared to the fence array. There is also some probability that sand particles can be saltating at heights greater than 0.3 m, but the probability of sand saltating higher than the 1.22 m high fences is much lower. Another difference is that a fence slows the flow along its entire length forcing it upwards. In the case of solid roughness elements in a staggered array, the flow can re-route between elements for several rows into the array before it starts to acquire near-equilibrium characteristics.

4.3. Sand fence array effect on PM10 concentrations

The delta changes in PM10 concentration between pairs of measurements at the fence array and south of the fence array absent any fences (Fig. 11) demonstrate most clearly for May 2015 that the fence array affected the PM10 in the atmosphere at this localized scale. In the absence of the sand fence array over approximately equal fetch distances, the concentration of dust at the reference sampling height above the surface increased with downwind distance, although the observed relative difference decreased for similar wind speeds between consecutive months.

An increase in PM10 concentration between E3 and E4 is consistent with the physics of wind erosion, where a fetch effect has been theorized (Owen presented in Gillette et al., 1996) and observed (Gillette et al., 1996; Gillette, 1999). The fetch effect is characterized as the increase of sediment mass flux with increasing downwind distance. The causes of this effect are multiple and include an avalanching mechanism, aerodynamic feedback, and a soil resistance mechanism (Gillette et al., 1996). At the ODSVRA sites there is an additional process that can cause an increase of sand flux in the west to east direction which is the increase in elevation from the shoreline through the dune complex. This rise in elevation compresses the streamlines of the air flowing increasing its speed, shear stress, and hence the sand flux (Wiggs et al., 1996). Gillies and Eyemezian (2014) observed this increase of wind speed (10 m AGL) measurements along linear transects. In the absence of physical obstructions (such as fence arrays) PM10 should increase with downwind distance as the dust emissions scale with the sand flux (Shao, 2000).

Our results suggest that the dust emissions associated with the saltating sand were modulated substantially by the fences due to reduced sand flux. Gillette et al., (1997) observed that for sandy soils the ratio of dust flux to saltation flux was relatively invariant. This linear coupling...
between sand flux and dust emissions suggests that the amount of dust flux reduction in the fence array is equivalent to the sand flux reduction. The reason that the change in PM$_{10}$ concentration does not match the observed sand flux reductions is that the site is embedded within a very large area of active dust emissions when the wind speed is above threshold for sand transport. The dispersion of dust from the surrounding dune environment is likely impacting the downwind monitor E2. That the difference is still observable in this restricted area suggests that the flux of PM$_{10}$ from within the fences was reduced substantially.

5. Conclusions

The effectiveness of two arrays of sand fences of the same height, but with different inter-fence spacing, to reduce sand flux was examined at test sites in the ODSVRA, Oceano, CA. Measurements of sand flux through the arrays indicated that fences with a spacing of 7 h reduced sand flux by 78% considering the entire area within the perimeter, and by 86% for the areas that were >27 fence heights from the leading edge of the array. For fences spaced at 10 h sand flux was controlled for the entire area by 40%. At distances >93 fence heights, which was 62% of the total area, sand flux was reduced by 56%. There was a substantial increase in control effectiveness achieved by moving the fences closer together. The degree of control achieved by the 7 h and 10 h fence spacings was less than predicted by the model developed by White et al. (2003), but this may be due, in part, to the variable wind direction and complex topography of the dunes compared to the flat surface the model was developed for. If the model of White et al. (2003) were to be used, caution is suggested for application in a dune environment and the assumptions used should be very conservative.

As previously observed for arrays of three dimensional roughness elements and similarly for sand fences, sand flux decreases exponentially with increasing distance into the array until an equilibrium flux is reached. The data from this study of multiple fences suggests that the rate of change of the decrease in sand flux is controlled by the spacing between the fences. The 1.22 m high fences, for an equivalent amount of sand flux reduction that could be achieved using the roughness element array approach, reduce the sand flux as it enters the fences at a faster rate than 0.3 m high roughness elements. Scaled by the height of the obstruction the distance to the equilibrium flux is

\[ \text{Distance} \approx \text{Height}^2 \]

The dispersion of dust from the surrounding dune environment is likely impacting the downwind monitor E2. That the difference is still observable in this restricted area suggests that the flux of PM$_{10}$ from within the fences was reduced substantially.

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References


