Dust Control Projects ODSVRA, 2018 (DRAFT)

J.A. Gillies, V. Etyemezian, G. Nikolich
Division of Atmospheric Sciences, Desert Research Institute, Reno and Las Vegas, NV

Draft date: 01/19/2018

Introduction

Since 2014 California State Parks has installed control measures including sand fence and roughness arrays to temporarily reduce, and planted vegetation in critical areas to eliminate, sand transport and the associated dust emissions in areas of the Oceano Dunes State Vehicular Recreation Area (ODSVRA) State Park. These control measures are emplaced to try and reduce the amount of particulate matter ≤10 μm aerodynamic diameter (PM_{10}) originating from within the ODSVRA due to wind erosion that is part of the overall PM_{10} burden measured at air quality monitors operated by the San Luis Obispo Co. Air Pollution Control District (SLOCAPCD). The air quality management objectives that the mitigation measures are trying to achieve are SLOCAPCD's Rule Dust Rule 1001 and to reduce contributions of PM_{10} originating from within the ODSVRA to try and keep the 24-hour mean PM_{10} measurement below the federal (150 μg m^{-3}) and state (50 μg m^{-3}) standards.

Arrays of sand fences of varying size (15 to 40 acres) have been installed each year within the ODSVRA beginning in 2014. In 2014, 4 foot-high plastic sand fences of ≈50% porosity were emplaced into ≈30 acres of dunes. They were oriented approximately perpendicular to the prevailing direction of high wind and spaced 10 fence heights apart (10h). In 2015 the same type of fencing was emplaced in ≈37 acres, but the spacing was reduced to 7 fence heights apart (7h). Gillies et al. (2017) report on the effectiveness of these arrays of porous fences to reduce sand flux and dust emissions. Measurements of sand flux through the arrays indicated that it diminishes exponentially with increasing distance, reaching equilibrium at ≈93 fence heights for the 10h spacing and ≈27 fence heights for the 7h spacing. Fences spaced 7h apart reduced sand flux for the entire area by 78%, and 86% for the area that was a distance of >27 h from the leading fence. Fences spaced at 10 h reduced sand flux for the entire area by 40%, and 56% for the area >93h downwind from the leading fence. PM_{10} monitoring upwind and downwind of the array and in the absence of the array in 2015, indicated that the downwind PM_{10} concentration was less than the upwind for the fence array, whereas in the absence of fences PM_{10} increased in the downwind direction over the same fetch distance, suggesting the presence of the fences was reducing the flux of PM_{10} from within the fence array. A reasonable estimate of the reduction in dust emissions attributable to the fence arrays is that is equivalent to the reduction achieved in the sand flux, as for sandy soils it has been observed that the ratio of dust flux to sand flux is relatively stable and independent of wind speed (Gillette., 1999).

Information from the 2014 and 2015 studies (Gillies et al., 2016; 2017) was used to guide the dust control approach for 2016. In spring 2016 an array of sand fences was re-established within the ODSVRA with the fence-to-fence distance set at 7h that covered 40 acres. In 2016 the target for sand flux reduction was expected to be close to that observed in 2015 (i.e., 73% [±22%] lower compared to sand flux external to the array for entire array) as the fence spacing was the same. The 2016 sand flux data indicated that the sand transport reduction for the entire surface area defined by the perimeter of the array was 73% (±80%), which is the same as the 2015 percent reduction in sand flux, but with a much higher variability. There was also good evidence from the PM_{10} measurements that the dust plume travelling over the array again showed quantifiable reductions in PM_{10} concentrations due to the controls (Fig. 1). Based on the reported effectiveness of the 7h sand fence array to reduce sand transport to levels >70% after the adjustment of sand flux to the presence of the fences, a sand fence array was emplaced within the ODSVRA in 2017 at a different location than in previous years. The 2017 location was demarcated based on information gained from the dispersion modeling carried out by the California Air Resources Board in 2016/2017 that identified the relative contributions of specified areas of the ODSVRA to the PM_{10} measured at the CDF SLOCAPCD monitoring site. In 2017 the sand fence array was emplaced within an area that the dispersion model suggested had a greater probability of contributing PM_{10} at the CDF site than the areas targeted in previous years.

A brief overview of the data collected in 2017 to characterize the sand flux as modulated by the presence of the sand fence array is provided below. The 2017 sand flux data indicate that the sand transport reduction for the entire surface area defined by the perimeter of the array, when sand flux measured upwind of the array resulted in sand catches in the single-height BSNE traps ≥10 g was 45% (±100%), which characterized days with the highest sand flux rates. The mean normalized sand flux (i.e., NSF=sand flux interior the array/sand flux exterior to the array) plotted as a function of distance from the front of the array shows that there were two positions that recorded NSF values that were much greater than the flux exterior to the array (Fig. 2). The two positions represent ≈12% of the total. Removing these two positions, the mean NSF becomes 0.24 (±0.25), which is a reduction in sand flux of 76% (25%) over 89% of the sand fence array, which matches quite closely the results of 2015 and 2016 for sand fence arrays spaced at 7h. A second set of multi-height BSNE traps (Gillies et al., 2013; Gillies et al., 2018) were also set into the fence array in 2017 to provide a second measure of sand flux reduction and to examine how the sand flux changes as a function of height above the sand surface. The multi-height trap data for days in which the mass of the single height BSNE measurement was ≥10 g show a similar pattern of changing flux with distance through the array, with a notable increase in flux at ≈110 m into the array (Fig. 2). The mean NSF for the all the multi-height BSNE traps was 0.46 (±0.48). Removing the high NSF at the 110 m position changes the mean NSF to 0.29 (±0.10), which is a mean sand flux reduction of ≈70% (±10%), which closely matches mean sand flux reduction value based on the single height BSNE traps.

Another difference in the 2017 NSF data set compared to 2015 and 2016, is that there is a suggestion of a trend of decreasing sand flux reduction with increasing distance into the array. This may be due to the increasing elevation of the surface towards the downwind edge of the array, which is likely causing an increase in wind speed that increases the sand flux. As the wind streamlines are compressed as the flow moves over the array towards the east, wind speed would increase. This can be evaluated further using the 2017 E-BAM data that is not yet available.

The objective to demonstrate that these control measures can reduce the PM_{10} at downwind monitoring sites to the desired air quality standards has not been unambiguously demonstrated at this time. The SLOCAPCD 2016 Annual Air Quality Report, based on their analyses of PM_{10}, wind speed and wind

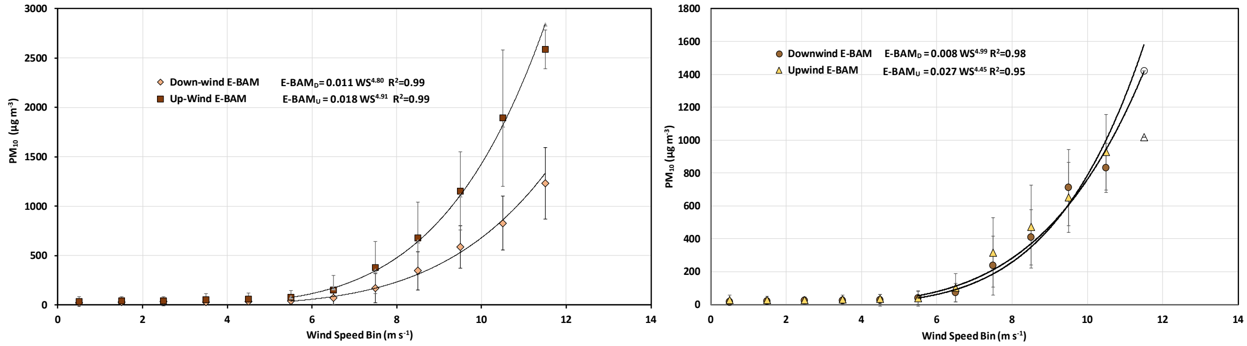

Figure 1. Mean hourly PM_{10} (µg m^{-3}) concentration plotted as a function of mean hourly wind speed (m s^{-1}) for upwind PM_{10} measurements (brown squares) and immediate downwind measurements past the sand fence array (gold diamonds) (left panel). Upwind PM_{10} measurements (gold triangles) and downwind measurements (brown circles) across approximately the same horizontal distance in the absence of fences (right panel). In all cases the data have been filtered for wind direction range 230°-310°), May through September, 2016. Best fit regression lines are for wind speed ≥5.5 m s^{-1} and the error bars represent the standard deviation of the mean for the data that fall into the 1 m s^{-1} wind speed bins.

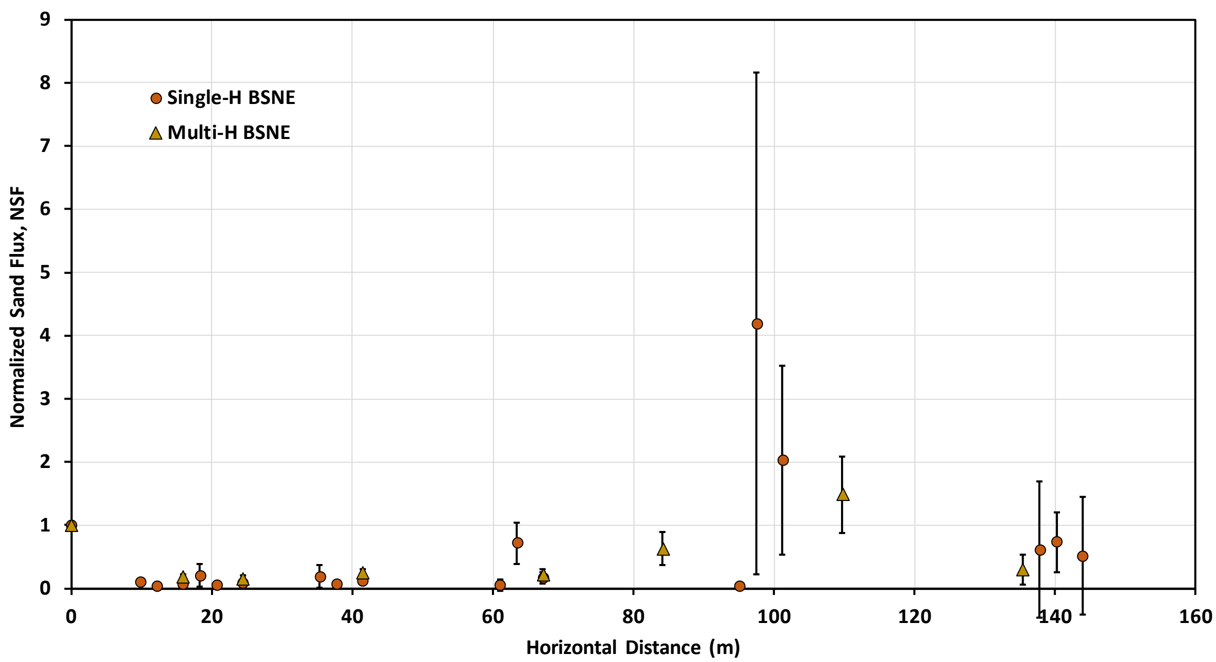

Figure 2. The normalized sand flux as a function of distance through the sand fence array for 2017 based on the measurement of sand using single-height and multi-height BSNE traps. Error bars represent the standard deviation of the mean based on multiple samples.

direction data measured at the CDF monitoring site does suggest that the 2016 dust control projects were "indeed somewhat effective in reducing PM_{10} at CDF", which is based on analysis using their filter days methodology, but they do not endorse this as being a definitive demonstration of an observable downwind effect. To achieve a demonstrable effect on downwind PM_{10} concentrations in the vicinity of the Nipomo Mesa may require an increase in the size of the area placed under control and a further optimization of the placement of the controls with respect to the areas of emission that have the highest probability, based on modeling, to be contributing to the PM_{10} burden downwind of the ODSVRA.

In 2018 California State Parks plans to initiate another combination of 1) a temporary dust control project within the ODSVRA using an array of sand fences placed 7h apart for two areas, one ≈30 acres and the other ≈10 acres (Fig. 3), 2) a vegetation planting project that will place plants in two areas totaling ≈18 acres (Fig. 3), and 3) an Operational Mitigation (OM) project that would use a combination of administrative controls on the camping area to achieve dust control. The objective being to reduce emissions that impact the downwind areas that experience high dust concentrations as a result of windblown emissions from the ODSVRA.

Metrics for gauging how well the 2018 control areas reduce PM_{10} at the scale of the control measures will be evaluated based on the amount of sand flux reduction that is observed between the uncontrolled upwind side and that observed within the area controlled. As a measure of the effect of the control measures on PM_{10} in their immediate vicinity, measurement of PM_{10} will be made on their upwind and downwind edges to evaluate change associated with the presence of the controls. A second pair of PM_{10} measurements will be made over a similar length of dune area in the absence of controls for comparison. In addition, a network of seven PM_{10} samplers will be operated, as they were in 2017, to measure PM_{10} in the ODSVRA, near the eastern park boundary, in the Conoco-Philips property upwind of the CDF site and at the CDF site. This network will provide insights into the spatial and temporal patterns of PM_{10} during wind dust emission events in 2018 that can be compared and contrasted with the patterns observed in 2017 that had a different amount and configurations of dust control measures.

To determine if there is an observable effect on PM_{10} due to the presence of the controls downwind of the ODSVRA, and at the kilometer scale of resolution, the number of exceedances of the 24-hour PM_{10} standard at the CDF monitoring site will be monitored and compared to previous years taking into account how the meteorology in 2018 compares to other available years. In addition, SLOCAPCD will carry out their filter day analysis method (SLOCAPCD, 2017) that evaluates the effect of the control measures on PM_{10} concentrations at CDF for specific ranges of wind speed, wind direction and durations of time for these conditions to last at a measurement position within the ODSVRA (i.e., the S1 tower) and at CDF. This method also requires that the data used have been validated by the APCD. The CDF site exhibits some of the highest concentrations of PM_{10} on the Nipomo mesa during windy periods and serves as an important indicator of the general air quality of the region.

In addition to using sand fences and vegetation to control sand movement, in 2018, a new strategy termed Operational Mitigations (OM) developed jointly by Parks and SLOCAPCD leadership will be evaluated as a dust control measure. OM will involve emplacing single (or multiple) rows of sand fencing in a strategic arrangement in areas where Park users prefer to camp. It is expected that the fencing and the camping accommodations will combine to provide a demonstrable reduction in sand flux and the accompanying dust emissions from areas that have been identified as being of high emission potential.

Dust Control Plan for 2018

For 2018 we propose that an array of sand fences with 7 fence height (7h) separation be established within the ODSVRA in the areas shown in Fig. 3. The areas selected for control are based on the available dispersion modeling carried out by the ARB, which attributes areas within the defined dust control areas as being significant sources of dust that contribute to the PM_{10} measured at CDF. As best as construction allows the bottom of the sand fence should initially be (a few inches) below the level of the sand surface to avoid flow acceleration under it, which reduces its effectiveness. If gaps in a row are required due to topography affecting placement of the fencing, the gap should be spanned with fencing placed downwind immediately as surface conditions allow, thus restricting fetch length between two sequential rows to the highest degree possible.

Sand Fence Array Location and Dimensions

Based on previous results that define sand fence effectiveness to reduce sand transport and the associated dust emissions it is recommended that the size of the sand fence array as shown in Fig. 3 be as large as is logistically feasible, with the assumption being that a larger size is better for two reasons: 1) more surface area in the ODSVRA is controlled, and 2) for larger areas the edge effect is reduced.

Recall that sand fence effectiveness at the upwind part of the array requires a distance of ≈27 h, when sand fences are spaced at 7h, to become fully adjusted to the presence of the fences. The larger the array, the smaller is the ratio of edge to equilibrium control area (Gillies et al., 2015). The same argument holds for horizontal gaps in the fences due to topographic constraints, these need to be a small as possible as they are less effective in reducing sand transport. To minimize edge effects, and the lower sand flux reduction associated with the equilibrium flux area, the shape of the array should be maintained to be as rectangular as possible.

Monitoring Effectiveness to Control Sand Flux in the Control Areas in 2018

In 2018 we recommend the monitoring of sand flux interior and exterior to the areas with controls applied using the 1-height self-orienting BSNE traps (Fryrear, 1986) for the sand fence array and vegetation areas, and the multi-height BSNE traps only in the sand fence array due to their limited number. If resources permit data collection should occur after each (assumed) daily transport event. All sand flux measuring instruments should be put in place as soon as possible after installation of the controls.

We recommend that for each area that receives controls, the BSNE traps be positioned through the array to determine the sand flux reduction levels as a function of distance through the controlled area. In each prior year of controls multiple measurements have been useful for defining the zone in which the sand flux adjusts to the presence of the roughness and the mean sand flux reduction in the zone where flux is adjusted to the presence of the roughness. In 2017, a new pattern of flux adjustment was

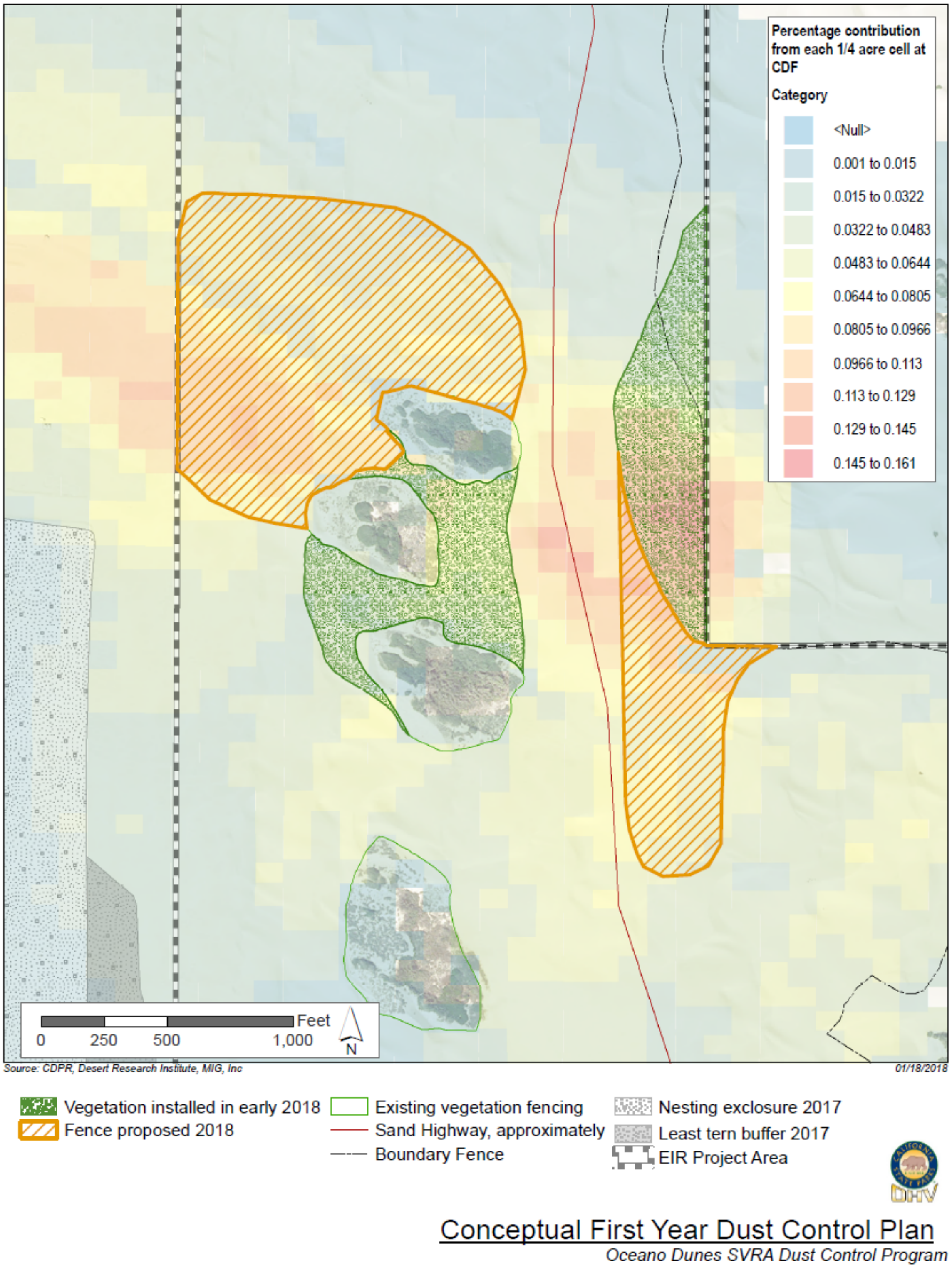

Figure 3. The proposed locations for the sand fence array (orange polygons with orange lines) and the two areas for vegetation planting (green stippled areas) in 2018. The underlying colors (blue to rose) identify the degree of fractional attribution of PM_{10} from a cell to the PM_{10} receptor at CDF.

observed, with one part of the array showing a noticeable increase in sand flux compared to the flux measured upwind and external to the array and the suggestion of a trend of increasing flux with increasing distance into the array at a distance >100 m. The flux increase at this position in the array (Fig. 2) we suspect is due to topographic forcing that has accelerated the wind speed.

If resources permit, we recommend that Parks make use of un-manned aerial vehicle (UAV) technology to repeatedly map the surface relief of the fence array using Light Detection and Ranging (lidar) techniques as attempts to use the photogrammetric technique in 2017 were found to be of limited use probably due to the weak color contrast across the dune surface. The acquisition of highly-resolved digital elevation models (DEM) of the control area made at the time of installation and during the period of emplacement will provide data to evaluate the total sand trapping potential of the array and provide information on the sedimentation processes that result from the fence position. Repeated mapping of the surface will allow for the determination of the patterns of erosion and deposition through the fence array. These can be linked with the sand trap measurements to provide a better understanding of the modulation of the sand flux by the fence array. These data are needed to guide engineering considerations to improve fence array performance as well as provide data to inform models that predict how porous fences affect airflow and sediment transport. Data from 2015 and 2016 suggest that sand transport and sand transport variability are greatest between consecutive fences at a distance of 3h behind the forward fence, which coincides with the transition at the surface from a zone of low turbulence to higher turbulence in McAneney and Judd's (1991) equilibrium flow model. Woodruff and Zingg (1955) observed a zone of maximum velocity fluctuations between successive fences at the 6h position, which doesn't match our observations. Neither McAneney and Judd (1991) nor Woodruff and Zingg (1955) measured sand transport.

In addition to these BSNE measurements, we propose to deploy 2 DRI-developed SANTRI™ saltation sensors that resolve sand flux using optical gate sensors (Etyemezian et al., 2017) at 1 Hz resolution and also resolve which direction the sand is coming from. We propose these stand-alone units be deployed between successive fences deep in the array to provide new information on the directional variability of sand flux with respect to the measured wind direction upwind and downwind of the array.

Sand Fence Array and Planted Vegetation Effect on Local PM_{10}

E-BAMs to measure PM_{10} should be positioned upwind and immediately downwind of the locations where controls are placed, and mounted so their collection orifices are all at the same height above the surface. The E-BAMs should be, as near as possible, along the center line of the controlled areas. The relationship shown in Fig. 1, suggests that PM_{10} immediately downwind of the fence array was ≈47% lower than measured at the upwind position. It is recommended that the E-BAMs be emplaced into their positions before the fences are installed, which would provide an opportunity to acquire measurements of the PM_{10} gradient across the space without controls, which could subsequently be compared to that gradient in the presence of the controls.

We also recommend that two E-BAMs be used in 2018 to measure the change in PM_{10} across a horizontal distance approximately equivalent to the length of the fence array in the absence of the fences. This will provide additional information how the presence of the fences affects the gradient of PM_{10} and the emission of PM_{10} from within the controlled area. In the absence of fencing over a similar horizontal distance the downwind measurement of PM_{10} is 22% higher than the upwind measurement. Upwind and immediate downwind monitoring of PM_{10} should also be carried out at both of the vegetation planting locations.

We recommend that the E-BAMs to be deployed within the ODSVRA be collocated with a BAM, preferably at the CDF site before and after the temporary controls are emplaced in 2018.

Additional PM_{10} Monitoring within and exterior to the ODSVRA

We also propose that the Met One monitoring network be re-established in 2018. The data collected by the network in 2016 and 2017 was of very high quality and will be quite helpful when data are needed for comparison to model results. We propose that the network be replicated in 2018 for complete spatial compatibility with the 2016 and 2017 network (Fig. 4), with the addition of a monitoring location added at the downwind edge of the 30 acre fenced area co-located with the E-BAM. Ideally, the network would be emplaced early in the dust season so that a longer record of data would be available. We recommend that all the monitors of the network be collocated with one another for a comparison prior to installation and at the end of the sampling season as was done in 2017. This colocation should again be carried out under controlled, indoor conditions at DRI's Southern Nevada Science Center facility in Las Vegas, NV, where we can be assured of a homogeneous aerosol concentration over a wide range and under relative humidity (RH) conditions similar to those that exist during windy season dust emissions events ($\approx$70%).

As the uncertainty in the attribution of an observable effect of the control measures on the PM_{10} concentration at CDF was high in 2016, care should be taken to have a much more complete data set on wind speed, wind direction, and PM_{10} for the control areas as well as at positions at other strategic locations within and exterior to the ODSVRA that are contemporaneous with the measurements at CDF. This will increase our ability to look at the links between the emissions from the Park during saltation and dust emission events.

Operational Mitigations (OM)

Operational Mitigations are based on the concept of incorporating sand fences to reduce sand flux into camping areas used by Park visitors, with the objective being that the physical presences of the fences and the camping vehicles will result in a sequestration of sand that becomes unavailable for driving dust emissions further downwind. The concept is based on the use of sand fences to reduce sand flux in the shelter zone of their lee and the camping units (tents, trailers, RVs) to act as roughness elements to aid in reducing wind speed. This method can be considered as being in the first phase of development and there is no a priori knowledge its effectiveness potential.

To evaluate the effectiveness of OM on an area of the ODSVRA, we suggest that the above mentioned lidar technique be used to estimate if sand is being sequestered in the area by determining if there is a net positive gain in surface elevation due to sand deposition following the lifetime of the OM. A lidar-acquired DEM would be needed prior to the establishment of the OM followed by a second measurement at the end of its temporary lifetime. This would require essentially excluding use of this area for a period of time to acquire the post-OM DEM. A measure of effectiveness could be estimated

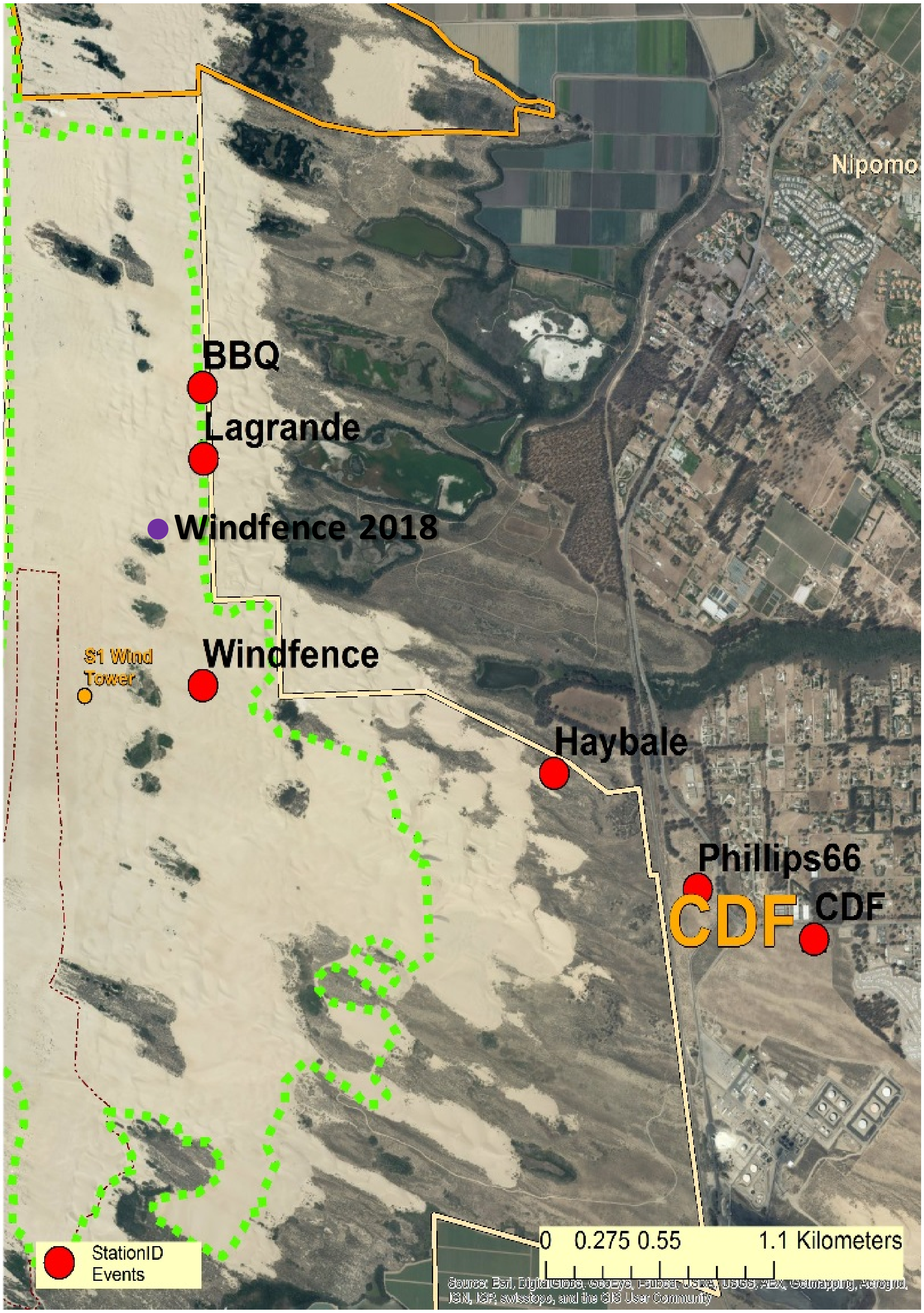

Figure 4. MetOne Particle Profiler stations 2016 & 17 marked as red circles. The stations positions should be the same for 2018 and a new position is recommended that is downwind of the 30 acre fence array (Fig. 3) shown as a purple circle.

from the mass of sand per unit area added (or lost) from the designated control area. If a loss of elevation was observed, this would suggest that OM had enhanced erosion, and dust emission. If there was a net gain of elevation and sand mass, this would indicate that sand was trapped within the OM area. The OM effectiveness, i.e., tons of sand added/acre, could be compared with the tons/acre added within the sand fence array. If the sand fence array added 10 tons per acre and the OM resulted in an addition of 5 tons/acre, the OM would be 50% less effective than the sand fence array at sequestering sand. If the sand fence array was demonstrated to reduce sand flux by ≈70%, as in previous years, then it could be inferred that, in this case, the OM reduced sand flux by 35%.

The ODSVRA Technical Team composed of personnel from Parks, DRI, SLOCAPCD, SLOCAPCD contractor, and California Air Resources Board are working to define the OM configuration and establish a measurement program to determine effectiveness for 2018. Installation of the OM will follow the completion of the installation of the 40 acres of sand fencing and the exclosure pilot test area.

PI-SWERL® Measurements 2018

PI-SWERL (Etyemezian et al., 2007, 2014) has been used extensively at the ODSVRA to characterize emission potential of the dust source areas. This has proved invaluable for generating a gridded emissions data base that can be used in dispersion models to generate predictions of downwind PM_{10} concentrations at specified receptors, and identify source areas that preferentially impact receptor sites. We propose to carry out measurements of dust emissions potential using PI-SWERL™ prior to the installation of the sand fence array, one month after full installation, and just prior to removal. We recommend, as has been done in previous years, that we measured emissions in the Plover exclosure area before it is closed to riding, and again subsequent to the re-introduction of driving.

New Opportunities

Moisture effects on PI-SWERL Measurements

One uncertainty that remains regarding the PI-SWERL measurements and related data is how much moisture affects the results of the measurement. Water is never too far beneath the surface of the sand dunes, but under certain conditions, the sand is moist even at a depth of one centimeter. We propose that a systematic evaluation of the effect of wetness be undertaken in DRI's environmental chamber. The intent would be to determine and separate the effect of ambient relative humidity from the effect of moisture content in the sand on the PI-SWERL measurement. This would be used to establish clear guidelines on when PI-SWERL testing should be conducted in the field and when it should be postponed until the sand is drier or the ambient relative humidity is lower.

Fencing an area to examine the effect of vehicle exclusion on sand transport

If it is logistically feasible, it would be instructive to fence off a section of the ODSVRA to OHV activity without emplacement of any other controls during the 2018 dusty season. At a minimum, the fenced off area would encompass 2 to 3 acres (Fig. 5). Lidar scanning of the area at the beginning of the windy season and near the end would provide significant insight into whether the absence of riding alone has afforded any dust control. Optionally, 1) one or both SANTRI devices could be emplaced within the

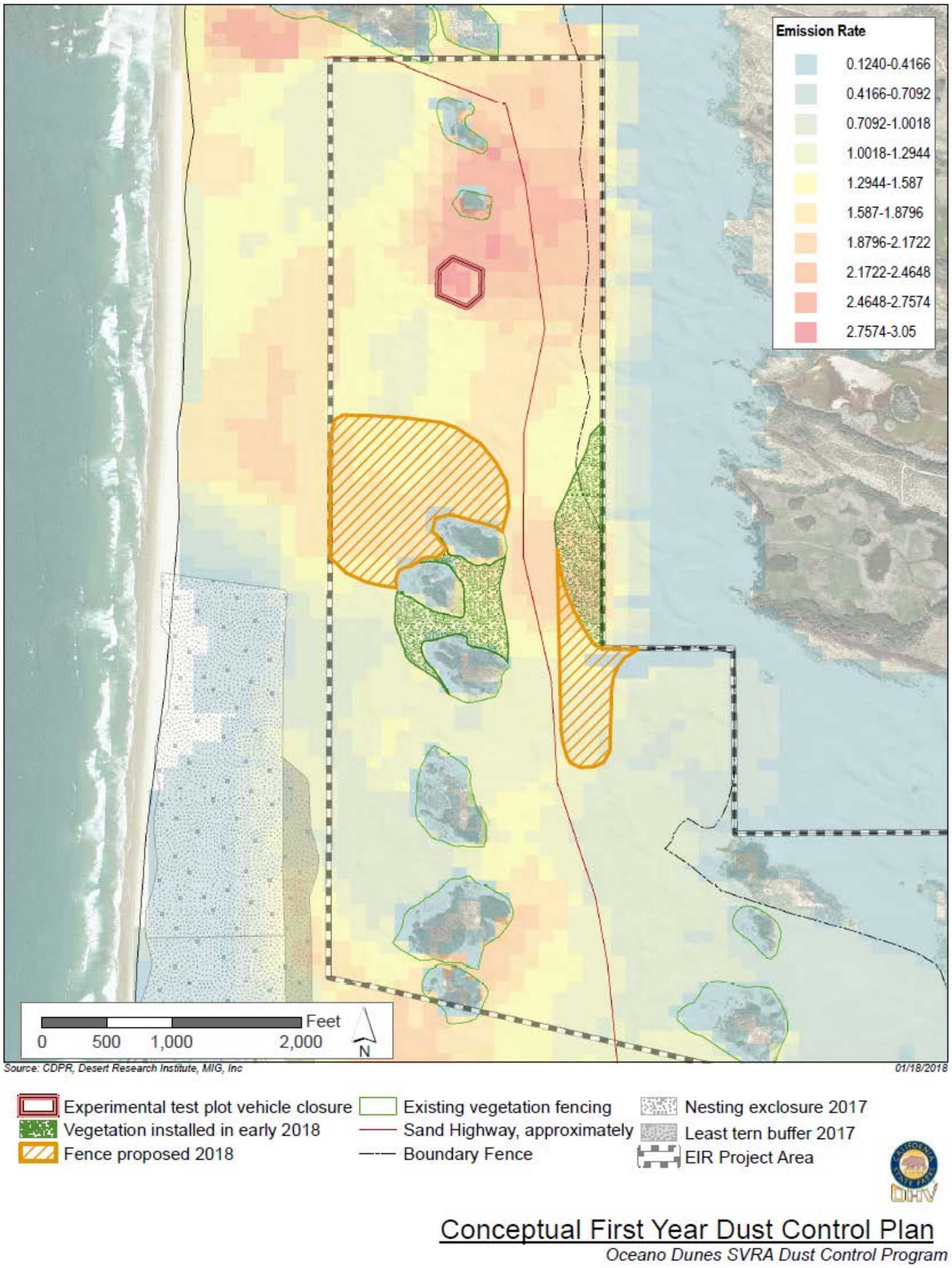

Figure 5. The proposed location of the OHV exclosure pilot test (red hexagon, not to scale of actual size to be created) with respect to the proposed locations for the sand fence array (orange polygons with orange lines) and the two areas for vegetation planting (green stippled areas) in 2018. The underlying colors (blue to rose) identify the emissivity of PM_{10} from a cell based on the interpolation/extrapolation of the 2013 PI-SWERL emission data.

fenced off area for data collection, 2) use a transect of single height BSNE sand traps to measure the sand flux from upwind (riding influenced) to the downwind edge of the exclosure. We also recommend that PM_{10} emissivity measurements be made with the PI-SWERL immediately following the construction of the exclosure and immediately prior to the exlosure being removed to determine if there has been any measureable change in emissivity that could be attributed to the restriction of OHV riding.

References

Etyemezian, V., G. Nikolich, W. Nickling, J.S. King, J.A. Gillies (2017), Analysis of an optical gate device for measuring aeolian sand transport, *Aeolian Research*, *24*, 65-79, doi: 10.1016/j.aeolia.2016.11.005.

Etyemezian, V., J. A. Gillies, M. Shinoda, G. Nikolich, J. King, A. R. Bardis (2014), Accounting for surface roughness on measurements conducted with PI-SWERL: Evaluation of a subjective visual approach and a photogrammetric technique, *Aeolian Research*, *13*, 35-50.

Etyemezian, V., G. Nikolich, S. Ahonen, M. Pitchford, M. Sweeney, J. Gillies, H. Kuhns (2007), The Portable In-Situ Wind Erosion Laboratory (PI-SWERL): a new method to measure PM_{10} windblown dust properties and potential for emissions, *Atmospheric Environment*, *41*, 3789-3796.

Fryrear, D. W. (1986). A field dust sampler. *Journal of Soil and Water Conservation 41*, 117-120.

Gillette, D. A. (1999). A qualitative geophysical explanation for "hot spot" dust emitting source regions. *Contributions to Atmospheric Physics*, 72 (1): 67-77.

Gillies, J.A., V. Etyemezian, G. Nikolich (2016). Analyses of Environmental Data Associated with the Sand Fence Array ODSVRA, 2016. Report Submitted to California State Parks, ODSVRA, Pismo Beach, CA.

Gillies, J.A., V. Etyemezian, G. Nikolich, W.G. Nickling, J. Kok (2018). Changes in the saltation flux following a step-change in macro-roughness. *Earth Surface Processes and Landforms* (submitted).

Gillies, J.A., V. Etyemezian, G. Nikolich, R. Glick, P. Rowland, T. Pesce, M. Skinner (2017). Effectiveness of an array of porous fences to reduce sand flux: Oceano Dunes, Oceano CA. *Journal of Wind Engineering and Industrial Aerodynamics, 168*, 247-259, doi: 10.1016/j.weia.2017.06.015.

Gillies, J. A., W. G. Nickling, M. Tilson (2013), Frequency, magnitude, and characteristics of aeolian sediment transport: McMurdo Dry Valleys, Antarctica, *Journal of Geophysical Research: Earth Surface*, *118*, 1-19, doi: 10.1029/2012JF002473.

Gillies, J. A., W. G. Nickling, M. Tilson, E. Furtak-Cole (2012), Wind-formed gravel bed forms, Wright Valley, Antarctica, *J. Geophys. Res.-Earth Surf.*, *117* (F04017), doi: 10.1029/2012JF002378.

McAneney, K. J., M. J. Judd (1991), Multiple windbreaks: An aeolean ensemble, *Boundary-Layer Meteorology*, *54* (1-2), 129-146.

SLOCAPCD (2017). Annual Air Quality Report 2016. Air Pollution Control District San Luis Obispo County, 3433 Roberto Court, San Luis, California, 93401.

Woodruff, N. P., A. W. Zingg (1955), A comparative analysis of wind-tunnel and atmospheric airflow patterns about single and successive barriers, *Trans. Am. Geophys. Union*, *36* (2), 203-208.