Using Roughness (Solid Elements and Plants) to Control Sand Movement and Dust Emissions: Keeler Dunes Dust Demonstration Project, Interim Report

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Introduction

The delivery of dust-sized particles to the atmosphere is an aerodynamically-driven process. There is a complex interplay, however, between the resisting and driving forces that control the release and entrainment of these particles and the vertical flux of dust. The dust can be entrained from soils when the surface is susceptible and the shearing force of the wind is sufficient to entrain particles. Entrainment of dust into the wind also occurs when sand-sized particles transported by the wind (saltation) impact the surface and eject dust sized particles. Dust can also be released to the airflow as aggregates of sediment breakdown during the vigorous transport process. Developing effective controls for dust emissions at the local and regional scales is a scientific and engineering challenge and demanding of attention due to the effects of dust on human and animal health, visibility degradation, and other negative environmental impacts.

Recent research has indicated that roughness can be used effectively to modulate sand transport (and the associated dust emissions) and that prediction of sand flux reduction using the known geometric properties and the amount of roughness is possible using published relationships (e.g., Gillies et al., 2007; Gillies and Lancaster, 2013). Great Basin Unified Air Pollution Control District, based on sand flux and associated dust emission measurements, developed a sand flux reduction criterion for the Keeler Dunes that, if attained, is expected to achieve PM_{10} levels within the town of Keeler, CA, in compliance with State and Federal Air Quality regulations. The sand flux reduction target is 95%, which infers that sand flux within the area of control must be reduced to 5% of the flux that occurs in the absence of controls within open dune areas. The initial target of 95% reduction of sand flux was changed to 85% due to problems in receiving the contracted for amount of roughness elements, but this does not diminish the veracity of the testing procedures to demonstrate the effectiveness of the methodological approach to controlling sand transport and dust emissions.

Using the sand flux reduction criterion as a basis for designing effective dust control at the Keeler Dunes a dust control demonstration project was initiated within the Keeler Dunes in July 2013. This demonstration project will evaluate if the effectiveness of an array of roughness elements composed of solid elements and managed vegetation, which was designed based on published empirically-defined relationships between sand flux reduction and a dimensionless index of roughness (i.e., roughness density [λ]) achieves the required sand flux reduction. This project has two major goals: 1) to demonstrate that solid roughness elements placed on areas of the Keeler Dunes immediately arrest sand movement to specified levels, and 2) to assess whether native plant species, planted in the sheltered area of the solid roughness elements can effectively thrive and subsequently replace the solid roughness to achieve the desired sand flux reduction control efficiency.

This component of the report focuses on evaluating the effectiveness of the solid roughness elements to modulate the sand transport.

Methods

The solid element roughness used in the Keeler dust control demonstration project is straw bales. The straw bales are nominally 1.12 m long × 0.38 m high × 0.43 m wide. To create a roughness configuration using this size bale and achieve the target sand reduction, the relationship between normalized sand flux (NSF) and λ presented by Gillies and Lancaster (2013):

$$NSF = 0.0004\,\boldsymbol{\lambda}^{-1.871} \quad (1)$$

was used to calculate the value of λ that would be required to meet the design criterion (i.e., NSF=0.15). NSF is defined as the ratio of sand flux at a measurement location within the roughness array divided by a measurement external to the roughness on the upwind side. The roughness density (λ) is defined as:

$$\lambda = n\, b\, h \,/\, S \quad (2)$$

where n is the number of roughness elements occupying the ground area S (m^2), b is element breadth (m), and h is element height (m). A value of $\lambda = 0.053$ is needed, which required 502 bales be placed in the defined test area (50 × 100 m).

The positioning of the straw bales within the test area was established by copying a natural vegetation pattern nearby the Keeler Dunes composed of the species: x, y, and z. First, the spatial pattern was transferred to a representative model area of the same relative dimensions as the field scale area. Then the transferred pattern was adjusted in scale until 502 points fell within the scaled rectangle representing the field site. Each point within the scale model was ascribed a position (i.e., latitude and longitude) allowing these positions to be marked in the test plot area at the Keeler Dunes. Upon delivery of the straw bales to the site a bale was placed at each marker with the longest bale dimension oriented perpendicular to the expected mean prevailing wind directions. In this area winds with the highest frequency and magnitude that cause sand transport and dust emissions come from both the north and south. The centerline of the roughness array was oriented to 326°, to best capture the sand transport events driven by the bi-modal wind regime.

The test area was instrumented to measure: 1) sand flux external and internal to the array, and 2) wind speed and wind direction external and internal to the array. A diagram of the position of the instruments and the type of measurements at each position is shown in Fig. 1. Sand flux is measured using the GBUAPCD-designed Cox Sand Catcher (CSC) (Fig. 2), which is used on Owens Lake for the GBUAPCD Dust ID project. In addition Sensit piezoelectric saltation sensors (Fig. 2) are used to measure the on-set of saltation external and internal to the array, and the counts of sand particle impacts provides a second means to calculate NSF at each Sensit position within the roughness. Wind speed and direction are measured using NRG anemometers and wind vanes mounted on 4 m high masts (Fig. 3).

To further evaluate the movement of sand into and within the roughness array detailed topographic surveys of the sand surface and the straw bales are being collected through time using Terrestrial Lidar Scanning techniques (Fig. 4). This laser-based surveying method produces three-dimensional surface elevation data that can be used to map where sand deposits and agrades or erodes and deflates from

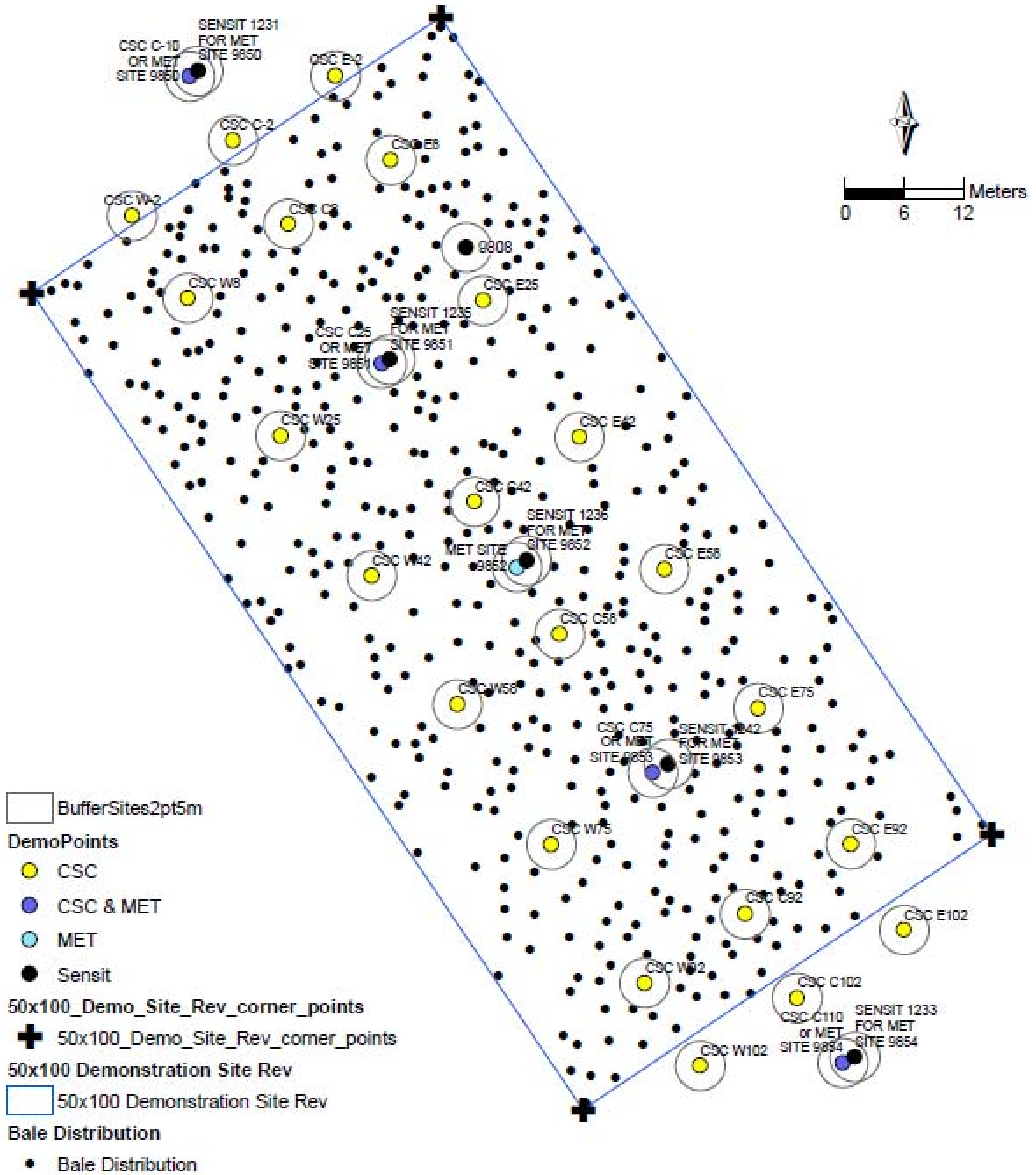

Figure 1. Schematic diagram showing placement of the roughness elements and instruments within the dust demonstration test are.

Figure 2. An image of a Cox Sand Catcher (left edge of image) and a Sensit piezolelectric saltation sensor (right edge of image) deployed within the roughness array.

Figure 3. The straw bale roughness elements and the 4 m high meteorological towers with anemometers and wind vanes.

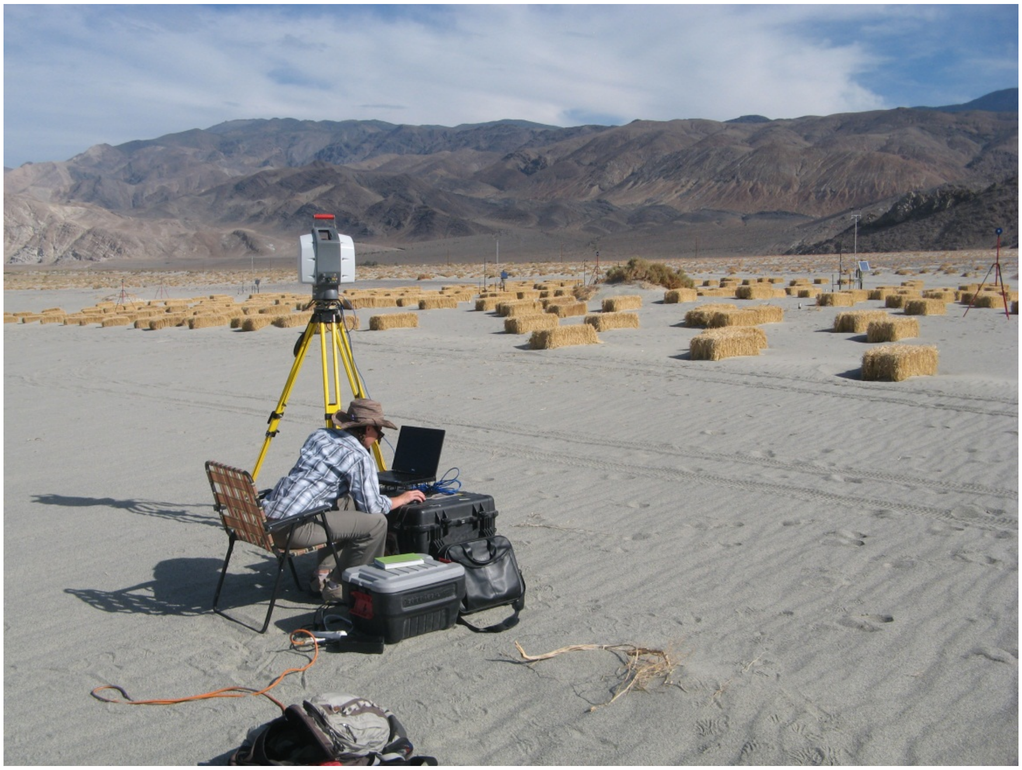

Figure 4. The Terrestrial Lidar Scanner deployed at the Keeler Dunes dust demonstration field site, September 11, 2013.

the test surface under the influence of the winds that exceed threshold. To date two scans of the test area have been acquired in July and September, 2013.

Results (through August 7, 2013)

Initial Sand Flux Measurements in the Presence of Existing Conditions Prior to Emplacement of the Roughness Elements and Vegetation

Prior to installation of the straw bales and vegetation CSCs were installed in a gridded array to measure the sand flux in the area where the roughness was to be emplaced. Measurements were initiated on 4/30/2013 and between that day and 5/22/2013, 18 events with the total mass in all traps ≥0.1 g were recorded with the CSCs. The mean NSF across each east-west grouping of CSCs as a function of distance from the leading northern edge of the roughness array is shown in Fig. 5. This figure shows that there was no discernible pattern in the transport of sand across the test site prior to emplacement of the roughness. The standard deviation of the mean NSF for each grouping of CSCs, represented by the error bars overlap for all cases, suggesting that within the uncertainty of the measurements sand flux was similar across and along the area in the presence of the roughness that existed prior to emplacement of the dust demonstration project roughness.

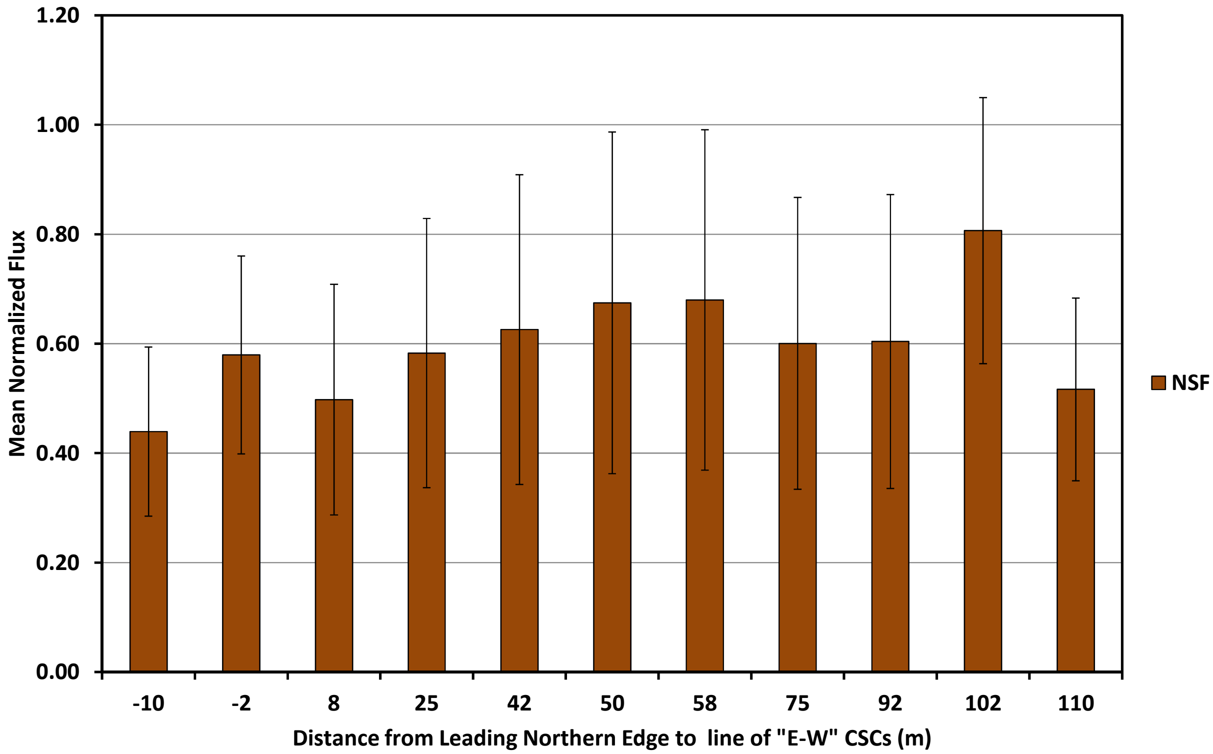

Figure 5. Mean NSF for the three CSC units across each east-west grouping CSCs as a function of distance from the leading northern edge of the roughness array.

Sand Flux Within and Exterior to the Roughness Array Following Emplacement of the Straw Bales

Following installation of the straw bales between 5/23/2013 and 8/7/2013, 74 transport events of varying duration and magnitude were recorded. The mean NSF as a function of normalized downwind distance (NDD=horizontal distance/element height) is shown if Fig. 6. As Fig. 6 shows the mean NSF decreases rapidly as a function of NDD from the north and south border of the roughness array to its interior. The mean NSF at the three positions at the deepest part of the roughness array (i.e., NDD=110.5, 131.6, and 152.6) is 0.06, suggesting that sand flux has dropped by 94% in the interior of the array compared to outside of the roughness array. The mean NSF value in the interior suggests that the roughness is performing better than expected. The roughness was expected to have an NSF=0.15.

These data can be separated based on the dominant transport directions, i.e., northerly and southerly wind events. The relationships between NSF and NDD for events representing transport events associated with northerly and southerly winds are shown in Figs. 7 and 8, respectively. For both transport directions the rate of change of decreasing NSF with increasing NDD is very similar, suggesting that there is no difference in the response of the sand flux to the roughness for either northerly or

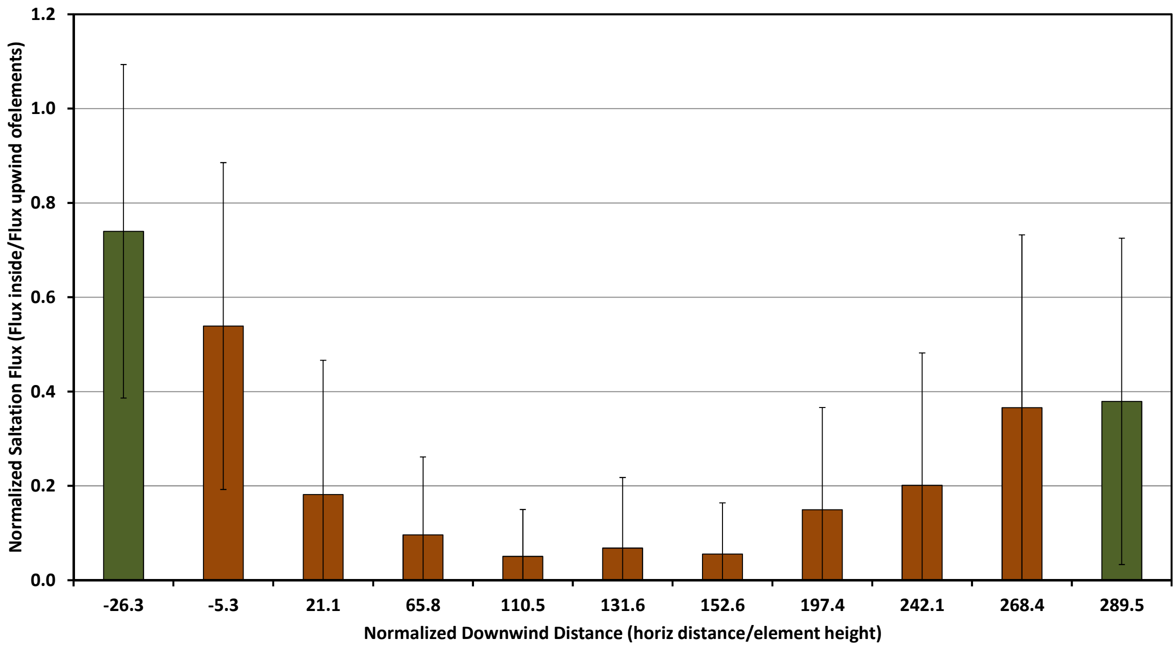

Figure 6. The mean NSF as a function of position within and exterior to the roughness array (refer to Fig. 1) showing that for all cases of sand transport the interior of the roughness shows a substantial reduction in the flux of sand. Green bars denote the two measurements exterior to the array on the northern and southern edges. Data represent transport of sand from multiple directions.

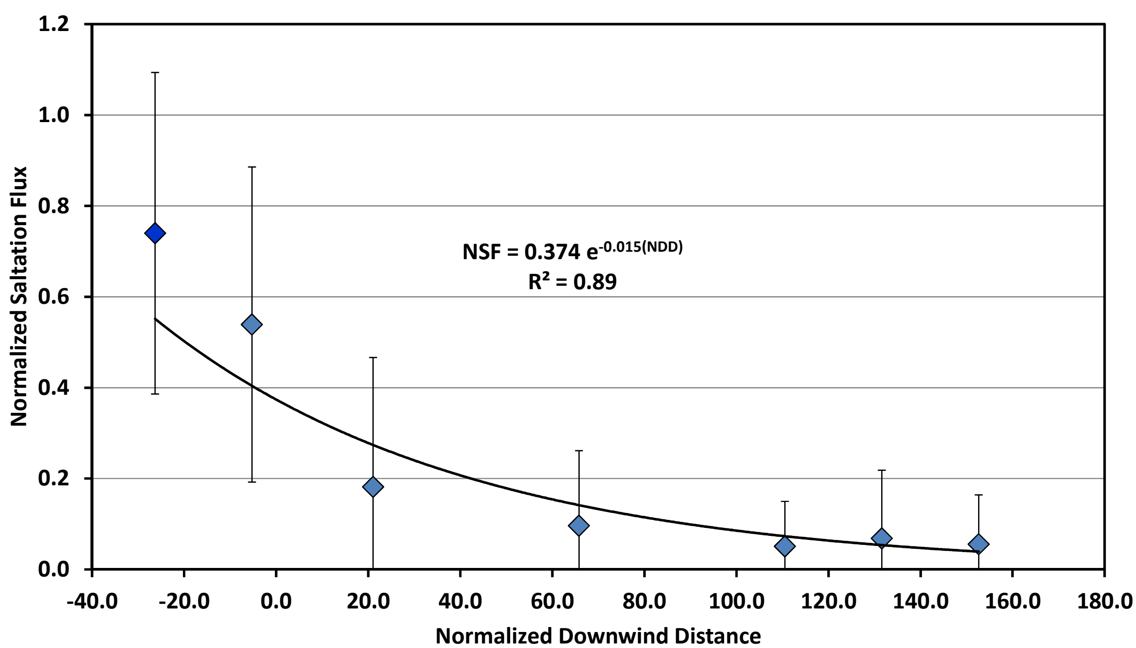

Figure 7. Mean NSF as a function of NDD for the north to south sand transport events. The dark blue data point on the left represents the measurement upwind and exterior to the roughness array.

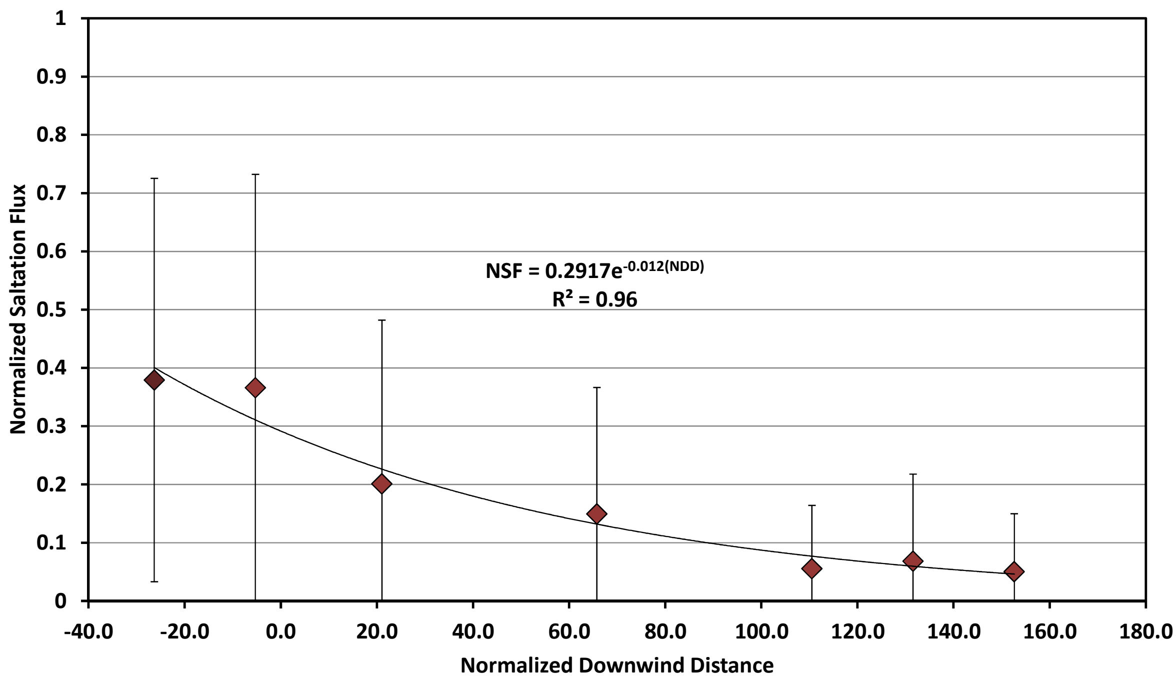

Figure 8. Mean NSF as a function of NDD for the south to north sand transport events. The dark red data point on the left represents the measurement upwind and exterior to the roughness array.

southerly transport events. The data can be combined into one general relationship showing how the NSF scales with increasing NDD into the roughness (Fig. 9).

The rate of change of NSF with increasing NDD for this project can be compared with other available studies (Fig. 10). This comparison of data shows that for the roughness array at the Keeler Dunes, the decrease in NSF with increasing NSF is less than has been observed at other locations. It must be noted that for Keeler Dunes the data collection to date is fairly limited and does not yet include any large scale and sustained transport events. The results to date indicate that the measured sand flux within the roughness is following expectations and corroborating the power of the empirical model used to design the array to meet the sand flux reduction target.

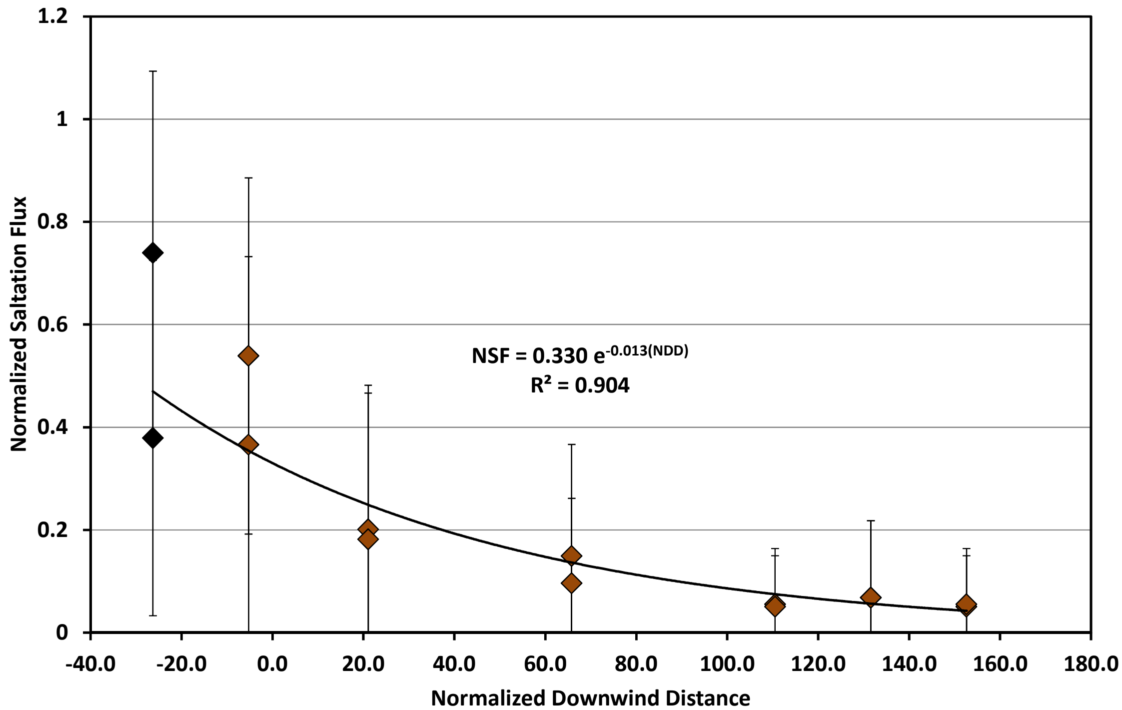

Figure 9. Mean NSF as a function of NDD for all sand transport events. The black points on the left represent the measurement upwind and exterior to the roughness array.

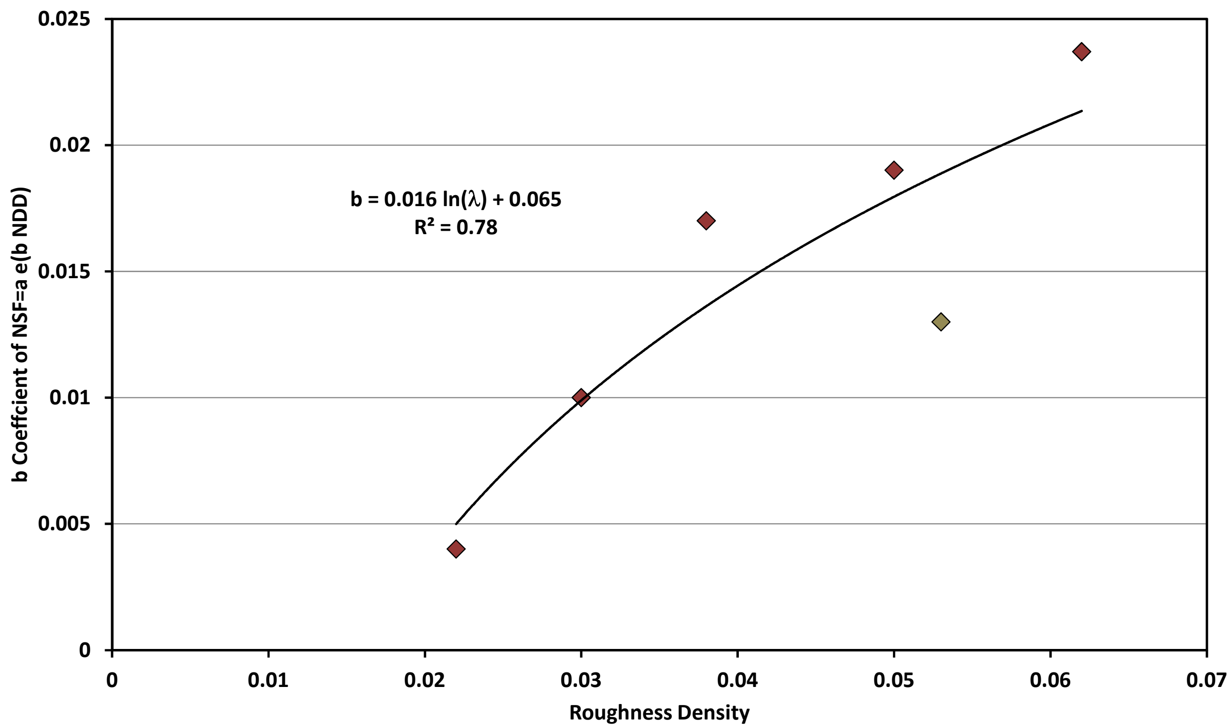

Figure 10. The relationship between the b coefficient in the NSF = a $e^{(b \times NDD)}$ and roughness density (λ) for data from Gillies et al. (2006) and Gillies and Lancaster (2013) and the roughness array at Keeler Dunes (green diamond). The regression-derived relationship combines all the data.

Wind Speed Threshold for Entrainment of Sand

The wind speed at which sand begins to be transported is an important environmental variable that characterizes the sensitivity of the sand surface to wind erosion and the accompanying dust emissions. Using the Sensit and wind speed data measured at 4 m above ground level (agl), an estimate of the threshold wind speed that causes entrainment of sand exterior and interior to the roughness elements at the study site. Threshold is defined here by the mean of all wind speed values that indicate saltation has been registered by the Sensit in the 5 minutes immediately following a 5 minute interval for which no Sensit counts were registered, and all wind speeds that show zero counts immediately following a 5 minute interval with counts. This takes into account the critical 5 minute long intervals where saltation begins and then ceases. The data are then sorted to represent the periods when the wind was northerly or southerly for each registered transport event. This procedure was carried out for days with measureable sand counts acquired by the Sensits. The mean threshold 4 m wind speed for each position along the centerline of the roughness for the southerly and northerly transport events is shown in Figs. 11 and 12, respectively. These figures show that the wind speed needed to reach threshold increases with distance from the leading edge of the roughness through to the last tower position before exiting the array. The relationship as expected is very similar for wind from both the south and the north. These figures illustrate several other important characteristics of the roughness array. First they show that once inside the roughness array it requires increasingly higher wind speeds to mobilize the sand, which means there is more protection afforded by this roughness configuration with distance from the leading edge. It also suggests that the size of the array does not allow the wind to come into equilibrium with the roughness over 75 m of fetch from the leading edge. The effect on threshold wind speed with increasing NDD is however, much less dramatic in affecting sediment transport rates than the roughness itself has on the change in flux rate (Figs. 7, 8, and 9).

Summary

The sand flux and wind data collected to date at Keeler Dunes Dust Demonstration Project clearly indicate that the straw bale roughness has modulated the sand flux compared to the flux in the absence of that roughness to a high degree. The mean reduction in the interior of the roughness array is approximately 94%, compared with flux in the absence of that roughness. To date the data suggest that the roughness is producing a higher control efficiency than the original design criteria specified.

The roughness also affects the threshold wind speed, showing that higher wind speeds as measured at 4 m above ground level are required to initiate saltation with increasing distance from the leading edge of the roughness. Based on measurements and visual observations it appears that the overall efficiency of this method to control sand movement and dust emissions increases with increasing area covered by the roughness elements. The edges of the roughness are most affected by higher winds and sand transport, but clearly the effectiveness to reduce sand motion occurs rapidly with increasing distance into the array. The perimeter to area ratio will decline as a power function meaning that the edge effect diminishes with respect to the effectiveness of control in the interior, so larger areas will have more area with maximum control efficiency for that roughness configuration than smaller areas. This also suggests that having higher roughness density around the edges can effectively increase overall control efficiency for smaller areas. These observations can be used to further increase the effectiveness of solid element roughness arrays to immediately arrest sand movement and dust emissions from the Keeler Dunes. This project will continue to collect data to refine the relationships and observations presented here.

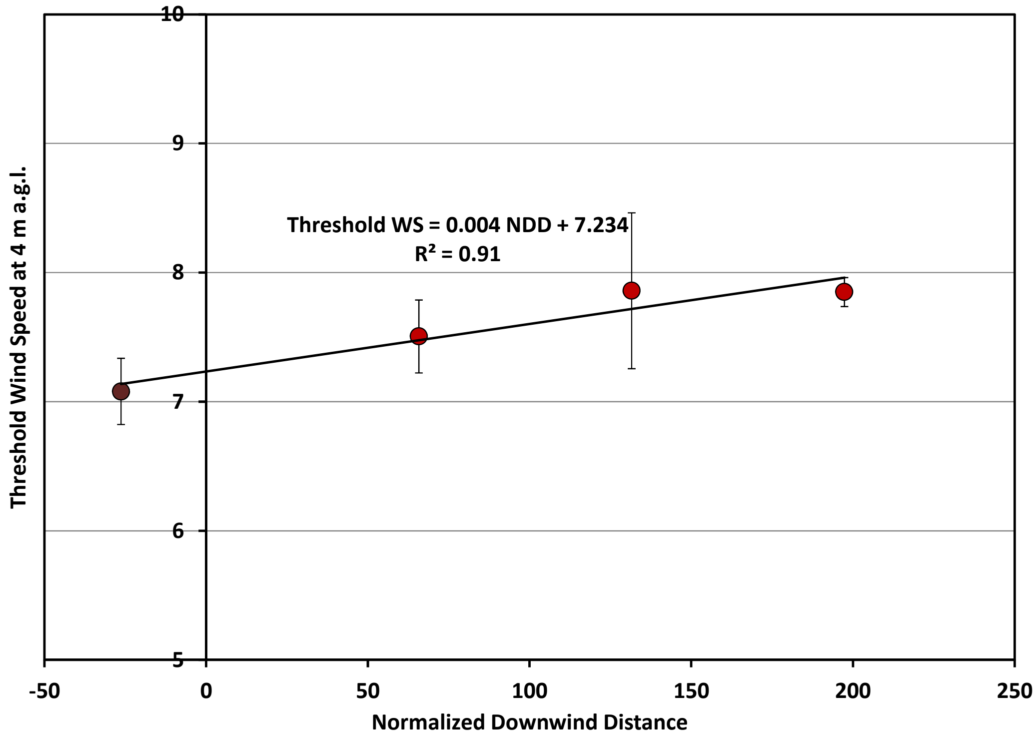

Figure 11. The relationship between mean threshold wind speed measured at 4 m a.g.l. and normalized downwind distance for southerly winds.

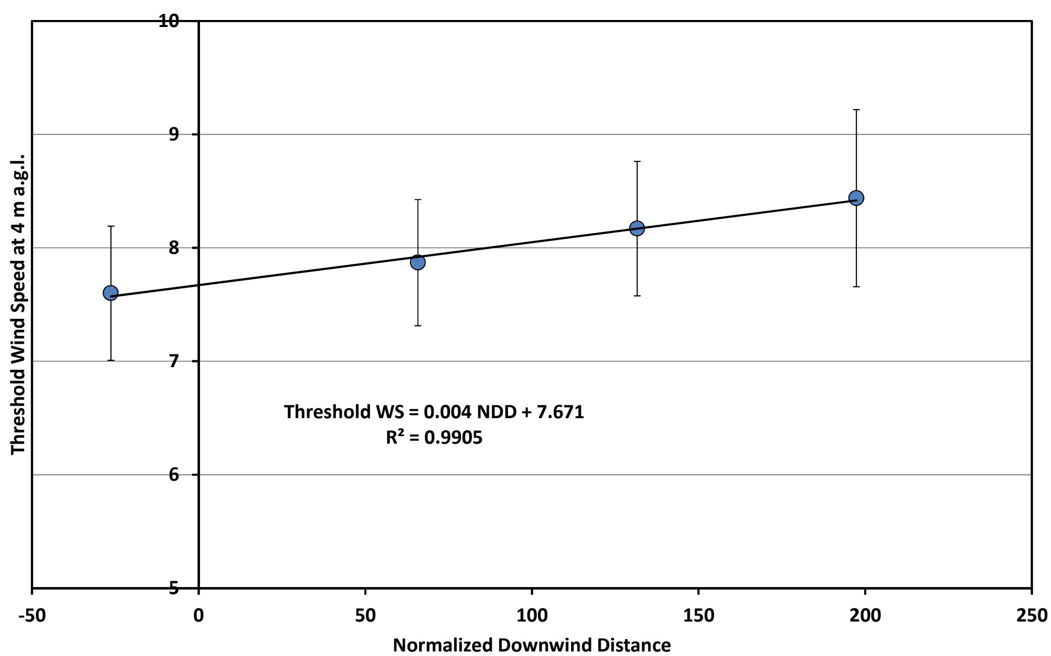

Figure 12. The relationship between mean threshold wind speed measured at 4 m a.g.l. and normalized downwind distance for northerly winds.