EVALUATION OF WIND EROSION CONTROL PRACTICES AT A PHOTOVOLTAIC POWER STATION WITHIN A SANDY AREA OF NORTHWEST, CHINA

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WIND EROSION CONTROL PRACTICES AT A PHOTOVOLTAIC POWER STATION

ABSTRACT

The widespread construction of photovoltaic (PV) power stations within northwest China poses an environmental threat because of severe wind erosion and land degradation attributed to unique wind control issues caused by the power stations. In this study, various engineering (E), plant (V), and biocrust (B) treatments were evaluated for their effectiveness in the reduction of wind erosion. The placement of solar panels with wide wind inlets and narrow wind outlets caused wind velocity reductions at the inlet that sharply increased at the outlet and formed distinct zones of deflation, direct shear abrasion (DSA), and deposition. The engineering treatments reduced the wind velocities and sand transport rates, in comparison to the control with E4 (DSA zone + a gravel/deposition zone + red clay) being the most effective with an 87% reduction in the total sand transport rate. Both plant treatments V1 (*Sedum aizoon* L.) and V2 (*Pennisetum alopecuroides* (L.) Spreng) increased the aerodynamic roughness, and decreased the sand transport rates and the sand erosion-deposition budget under or between the solar panels. Treatment B2 (moss crust) decreased the sand transport rate and sand erosion-deposition budget under the solar panels in comparison to the control. All the treatments had effects on reducing wind erosion, and we strongly recommend the use of moss crust, gravel mulch, and red clay mulch in the deflation zones, DSA zones, and deposition zones, respectively, to control the severe wind erosion at these PV power stations located in sandy areas.

KEY WORDS:photovoltaic power station; direct shear abrasion (DSA); deposition; biocrusts; wind erosion control

INTRODUCTION

Twenty-five percent of Earth’s land area is affected by land degradation that gives rise to a series of negative ecological and economical consequences, such as reductions in ecosystem services and corresponding degradation of ecosystem products, increased soil losses, water quality deterioration, biodiversity decline, and reductions of food production (Pacheco *et al.*, 2018). Ecosystem function impairments attributed to land degradation has caused average annual losses of $6.3 trillion US dollars in ecosystem service values (Sutton *et al.*, 2016). These losses stress the importance of restoring degraded lands and preventing the degradation of additional lands. Zero net land degradation (Land degradation neutrality, LDN) was developed as a target by the United Nations Convention to Combat Desertification (UNCCD) ( Sutton *et al.*, 2016; Chasek *et al.*, 2019; Gilbey *et al.*, 2019).

Wind erosion is a primary contributor to land degradation with one-third of the global terrestrial land areas impacted by wind erosion, particularly in arid and semi-arid land areas ( Zhang *et al.*, 2018; Chi *et al.*, 2019; Giménez *et al.*, 2019). Wind erosion interacts directly with the topsoil, where it depletes fine particles and associated nutrients, changes soil texture and soil particle size distribution, decreases nutrients and organic matter content, and amplifies the rate of water evaporation (Li *et al.*, 2009; Wang *et al.*, 2015; Yan *et al.*, 2013). These changes reduces the soil’s ability to resist erosion and increases the potential for additional soil degradation. Therefore, effectively reducing wind erosion can help mitigate land degradation.

Although there are various land management practices to reduce wind erosion, in Northwestern China the use of semi-buried sand barriers with materials of wheat, rice, reeds and other vegetative materials arranged in a checkerboard design is a cheap, effective, and widely used erosion reduction practice. This land surface practice reduces near-surface sand flow, stabilizes the sand surface through increasing topsoil roughness, reduces near-surface wind velocity, weakens the sand transportation rate, and changes the soil surface particle size distribution (Dai *et al.*, 2019; Liu & Bo, 2020; Qu *et al.*, 2007). Similar studies in the Taklimakan Desert demonstrated that wheat straw used in the checkerboard sand barriers may lower wind velocities by 33–90% and the sand transport rate by 60% (Cheng *et al.*, 2015; Tian *et al.*, 2015). Plant residue mulching and/or gravel mulch provides land surface cover that reduces the direct action of wind on the soil surface and is one of the more efficient practices to reduce soil and water erosion (Naghizade Asl *et al*., 2019; Prosdocimi *et al.*, 2016). The resistance ability of gravel mulch is related to its coverage, pebble size, and spreading methods. Roughness length increased with increased coverage from 5% to 15, but once the coverage exceeded 20%, the impacts on roughness length were approximately the same as having 0% coverage (Liu & Kimura, 2018). Decreased gravel sizes have been found to be negatively correlated with reductions in soil surface evaporation reductions in comparison to larger gravel sizes under similar soil moisture conditions (Yuan *et al.*, 2009). The various gravel spreading methods differ in their inhibitory effects on deflation, and when gravel coverage was 50%, the rank in terms of effectiveness was as follows: random spread > vertical strip spread > oblique strip spread > clustered spread > parallel strip spread (Liu *et al*., 1999). Gravel mulch has also been shown to improve soil productivity because the mulch may change the hydrological processes with increased soil nutrient contents, increased water infiltration, reduced evaporation, the trapping of dust particles, and enhanced biological activity (Li, 2003; Lv *et al*., 2019; Shojaei *et* *al.*, 2019). Plant cover practices were previously considered as the ideal practice since it affected the sand transport rate and the wind’s flow patterns (Lv & Dong, 2012). Li *et al*. (2007) and Zhao *et al*. (2005) reported that vegetation coverage and wind erosion are negatively correlated such that when the vegetation coverage is less than 20%, there is substantially greater wind erosion. A study of grasslands in southern Mexico indicated that herbaceous plants reduced soil erosion by wind and nutrient loss better than leguminous shrubs (Li *et al*., 2007). Wind tunnel studies have indicated that the wind erosion rate increased exponentially as vegetation coverage decreased (Dong *et al*., 1996, 2000a, 2000b). Under specific wind velocity conditions, the aerodynamic roughness z0 increased as plant density increased; and under other specific plant density conditions, z0 decreased with increased wind velocity in a pattern that resembles the response surface of exponential growth (Dong *et al*., 1996, 2000a, 2000b).

As an alternative method of wind erosion control, the rapid cultivation of biocrusts has been proven to be feasible and may be used as a practice for the short-term restoration of impaired ecosystems (Antoninka *et al*., 2016; Bu *et al*., 2014, 2015b; Doherty *et al*., 2015; Maestre *et al*., 2016). Undisturbed biocrusts were shown to inhibit wind erosion at wind velocities of 25–30 m/s (Wang *et al*., 2004). Thus far, engineering and plant practices have primarily been used for wind erosion control, whereas the use of biocrust practices has received limited scientific study.

The burning of conventional evergy has increased the atmospheric concentrations of greenhouse gases, which futher resulted in global climate warming. For sustainable development in the future, using renewables such as wind energy, solar energy, and nuclear energy is the key for reducing the production of greenhouse gases in energy production (Solaun & Cerdá, 2019). New energy industries have rapidly developed in China because of abundant natural resources. The development of solar photovoltaic (PV) power stations has rapidly increased and promises to be an attractive source of renewable energy. The cumulative installed PV power generation capacity of China reached 174 million kW by 2018, and within northwest China, the installed capacity of PV power stations has reached 50.03 million kW which is the greatest PV power generation capacity of any Chinese region (National Energy Administration, 2018). However, 95% of wind erosion has occurred in the arid/semiarid areas of China which is characteristic of large land areas within the northwest region (Chi *et al*., 2019). These areas have an arid climate, barren soil, sparse vegetation, and a fragile ecosystem; thus, large-scale disturbance and destruction associated with PV power station installation and operation have resulted in severe wind erosion hazards that pose a potential threat to the operation of the PV power stations and the already fragile sandy ecosystems. Compared to the traditional studies of wind erosion, the arrangement of the PV power stations with wide inlets and narrow wind outlets has changed the characteristics of the regional wind field and formed distinct zones of deflation and deposition that we have identified in Figure 1. There are deflation zones located under the solar panels that produce slight wind erosion on the surface layer. There are zones that are located at the base of the solar panels where the redirection of the prevailing wind has caused the formation of a V trench that is typically 1 meter wide and 1 meter deep at the outlet. We have identified these zones as direct shear abrasion (DSA) zones where the downward directed wind from the rear of the solar panel intersects the soil at the front of the solar panel and the shearing and abrasion effects of the wind causes a V trench to form. There are deposition zones located between the solar panels that are typically a stripped region 6 meters wide and up to 40 centimeters depth that forms between the outer edge of the DSA zone and the deflation zone under the next row of solar panels. Because of the severe wind erosion and land degradation that is currently occurring, there is an urgent need to establish a comprehensive erosion control system and to study the efficiency and mechanisms of erosion control for these PV power station areas. Unfortunately, existing knowledge of the patterns and/or control of wind erosion under natural conditions have not proven to be applicable to these PV power stations located in sandy areas. There are serious shortcomings in our knowledge concerning the wind velocity flow fields and wind erosion patterns surrounding the PV power stations, which makes it difficult to develop reasonable prevention measures to protect and sustain the fragile ecosystems. Only a few studies have investigated the patterns and characteristics of wind erosion at PV power stations in sandy areas, and the wind erosion control practices that were evaluated have rarely involved biocrusts. Through field measurements, Etyemezian *et al*. (2017) provided a ﬁrst-order estimation of the mean wind flows resulting from a utility-scale solar photovoltaic facility, which has been valuable for understanding these ﬂows and for checking the representativeness of wind tunnel measurements with numerical modeling results.

To address the serious DSA and deposition occurring between the solar panels, we evaluated various control treatments that included engineering, plant, and biocrust treatments. We measured the observed wind velocities, sand transport rates, wind-sand flow structures, wind profiles, wind velocity flow fields and roughness at fixed locations for a typical PV power station in a sandy area of northwest China. The primary objectives of this study were: (1) to explore the characteristics of the wind velocity flow field at the PV power station; (2) to determine the efficiency and mechanism of various protective treatments for erosion control; (3) to seek a protective treatment system for wind erosion hazards at the PV power station projects; and (4) provide a practical reference for wind erosion control in similar projects.

MATERIALS AND METHODS

*Study Area*

The study area is located on the southeastern edge of the Mu Us Sandland, in Dabaodang Town within southwestern Shenmu County of Shaanxi Province, China (38°41′31"N, 109°56′44"E). The average annual temperature is 8.9 °C, and the annual average rainfall is 437.8 mm with large inter-annual variations. Southeasterly winds prevail in the summer (July–September), and northwesterly winds prevail during the remainder of the year. There are frequent sandstorms, and the average annual wind velocity is 2.2 m/s, with a maximum of 3.0 m/s in April and a minimum of 1.7 m/s in September. The average seasonal wind velocities are 2.8 m/s in spring, 2.2 m/s in summer, 1.8 m/s in autumn, and 2.0 m/s in winter; thus, the wind velocities are highest in spring and lowest in autumn. The primary vegetation includes *Artemisia ordosica* and *Salix cheilophila Schneid*, with sparsely distributed *Phyllostachys propinqua*, *Hedysarum scoparium*, *Hedysarum fruticosum*, and *Setaria viridis* (L.) *Beauv* (Yuan *et al.*, 2016). The soil at the study site was derived from aeolian sand and loess. This location is associated with a geomorphologic transition from fixed–semi-fixed dunes to loess hills and typically has severe wind and water erosion (Jia *et al.*, 1993). There are also some limited agriculture, forestry, and animal husbandry activities practiced in this ecologically fragile zone. To achieve the highest photovoltaic power generation, the solar panels are aligned north and south with the active solar receptive surface facing south.

*Experimental Layout*

In August 2014, prior to the beginning of the study, every plot was leveled and restored to the original landforms to coincide with the construction completion of the PV station. Then engineering, plant, and biocrust treatments were placed in the deflation zone under the solar panels and in the DSA and deposition zones between the solar panels, the position and the relationship of the treatments are shown in Fig. 2 and described in Table 1. The five engineering treatments were only placed between the solar panels and included bare land control (E-CK), wheat straw checkerboard (E1), gravel mulch (E2), red clay mulch (E3), and combined practices (E4). Each experimental plot measured 18 m × 7 m and was divided into two parts: a DSA zone (1 m from the wind outlet) and a deposition zone (6 m from the wind inlet of the next row of solar panels). All the engineering treatments were placed in the DSA and deposition areas (Fig. 2). For the E1 treatment, the experiment plots were 18 m × 7 m, and the size of wheat straw checkerboard was 1 m × 1 m (Fig. 3b); for the E2 treatment, a layer of gravel 3–7 cm in diameter was placed on the surface (Fig. 3c); and for the E3 treatment, a layer of red clay 10 cm thick was placed on the surface (Fig. 3d). The E-CK, E1, E2, and E3 treatments were single practice treatments, while the E4 treatment was a combined practice treatment that consisted of gravel placed on the soil surface within the DSA zone and red clay placed on the soil surface within the deposition areas, respectively (Fig. 3e). The three plant treatments included natural vegetation restoration (V-CK, a few *Agriophyllum squarrosum* (L.) Moq. distributed sparsely), *Sedum aizoon L.* (V1), and *Pennisetum alopecuroides (L.)* Spreng.(V2). Each plant treatment was divided into two parts: under the solar panels (Fig. 3g) and between the solar panels (Fig. 3h). Bare land control (B-CK), algal crust (B1, Fig. 3j), and moss crust (B2, Fig. 3k) were the biocrust treatments that were placed on the soil surface under the solar panels. At the beginning of the study, wheat straw checkerboards were placed within the biocrust treatment plots to protect the growth and development of the biocrusts.

*Measurement Indicators and Methods*

Treatments were evaluated using two part indicator measurements. Efficiency indicators included wind velocity, wind velocity flow patterns, wind velocity profiles, and aerodynamic roughness (z0). Mechanism indicators included the sand erosion-deposition budgets, sand transport rates, and wind-sand flow structure.

The influence of solar panels on wind velocities were synchronously measured at 20 cm and 200 cm heights within the peripheral area and within the bare land area between the solar panels from 23/4/2015 to 26/4/2015. In the peripheral area, wind velocities were measured using a HOBO U30 meteorological station (Onset Computer Corporation, Inc.), which collected data in 1s intervals with the 10 min averages also being automatically recorded. Between the solar panels, an FR2030 profile wind velocity monitoring system combined with an FR3122 three-cup wind velocity sensor were used (Fig. 4a) (Onset Computer Corporation, Inc.), which collected data in 1s intervals with the 1 min averages also being automatically recorded. During the study, we obtained a total of 401 and 3903 wind datasets within the peripheral area and within the bare land areas between the solar panels, respectively.

The wind velocity flow field within the bare land areas was measured to determine the vertical variations of subsurface wind speeds under the influence of the solar panels using FR2030 profile wind velocity monitoring systems combined with FR3122 three-cup wind velocity sensors. Six groups of FR3122 three-cup wind velocity sensors were used to simultaneously measure the wind velocities at different heights around the solar panels (Fig. 4a). The highest measured height increased gradually from the wind outlet to the wind inlet. Measurements were taken 3 m from the front of the wind outlet where wind velocities at a 20 cm height were measured. As a point of reference, we took this position as the origin point (0,0) for the direction of wind outlet to wind inlet as a positive direction in 1-m intervals to describe the position of the other instruments in a detailed layout as follows: (1) At position (2,0), it was same as the origin point, with wind velocities measured at a 20-cm height; (2) At (4,0), 1 m behind the wind outlet, the wind velocities were measured at heights of 20 cm and 40 cm; (3) At (5,0), 2 m behind the wind outlet, the wind velocities were measured at heights of 20-, 40-, 60- and 80 cm; (4) At (6,0) , the wind velocities were measured at heights of 20-, 40-, 60-, 80-, 100-, 120- and 150 cm; and (5) At (9.5,0), 3.5 m behind the wind inlet, the wind velocities were measured at heights of 20-, 40-, 60-, 80-, 100-, 120-, 150- and 200 cm. There was a total of 23 FR3122 three-cup wind velocity sensors used to make simultaneous measurements from 23/4/2015 to 26/4/2015. Wind velocity measurements were also automatically recorded on a 1-minute basis and these measurements used to draw the wind velocity flow fields.

FR2030 profile wind velocity monitoring systems combined with FR3122 three-cup wind velocity sensors were set in every treatment between the solar panels to simultaneously measure wind velocities at heights of 20-, 40-, 60-, 80-, 100-, 120-, 150- and 200 cm (Fig. 4a). Measurements in 1s intervals and 1 min averages were automatically recorded, then the recorded data was used to draw wind velocity profiles and to calculate the aerodynamic roughness (z0). The parameter z0 refers to the constant of a geometric height with zero wind velocity, which varies with the ground surface roughness. We assumed that in neutral or near-neutral layers, the wind velocity within the surface layer presents a logarithmic relationship within the height distribution. Using the average wind velocities to calculate z0 can improve the reasonableness and accuracy of results (Yang, 1996). Therefore, the wind velocity profile and calculation of z0 were based on the average of 10 groups of data measured at 10-min intervals. The computation of z0 can be calculated from the average wind velocity profiles using the following equations (Dong *et al*., 2000b; Liu & Dong, 2003; Zhang *et al*., 2016a) :

 (1)

 (2)

Where u are the wind velocities (m/s) at heights z; *a* and *b* are the intercept and slope of the logarithmic function of the wind velocity profiles, respectively, and determined by means of least-squares curve fitting.

Three 10-step sand samplers were placed about one quarter, two quarters, and three-quarters of the distance along the axis within each experimental plot with the sand inlet of each sampler parallel to the wind direction (Fig. 4f). The sand sampler was similiar to the WITSEG sampler designed by Cold and Arid Regions Environmental and Engineering Research Insitute, Chinese Academy of Sciences (Dong *et al.*, 2004), and was a passive sampler. The height of the sand samplers was 25 cm and sectioned into 10 blown sand inlets, every inlet was 2.5×2.5 cm and connected with a sand chamber. To reduce the variability caused by the external environment, the sand mass of every sand sampler was randomly measured three times and considered the sum taken of three measurements. The sum of the three measurements of each sampler was used as a repeated measure to analyze the differences among different treatments. Each measurement period was 24 h and the mass of sand within each chamber was measured using an electronic scale with an accuracy of ten thousandths of a gram. The sand transport rate was obtained using the following formula (3) (Ma *et al.*, 2010).

 (3)

Where Q is the sand transport rate, g/(cm2·h); W is the sand mass in the sand sampler, g; a is the area of the sand sampler, 6.25 cm2; and T is the observation time, h.

The sand erosion-deposition budget refers to the difference between the accumulated amounts and the surface material blown away by wind in a certain time. Chain-pins, 60 centimeters in length, were used to measure the sand erosion-deposition budget, and were arranged uniformly after the application of all treatments to insure the consistence of the initial measured height and measured time.. Between the solar panels, the chain-pins were placed in 3 rows and 4 columns within the deposition zone and 30 centimeters vertically into the ground, with 6 chain-pins that were equally divided for placement within the DSA zone and 20 centimeters vertically into the ground (Fig. 4b). Under the solar panels, the chain-pins were placed in 3 rows and 3 columns, and 20 centimeters vertically into the ground. There were three repetitions in each experimental plot. The observed period of wind erosion was from October 15, 2014 to October 15, 2015. We measured the vertical length (H) of the chain-pins on the ground in order to calculate the sand erosion-deposition budget by “H”.

*Data analysis*

To explore possible differences in the sand transport rate, erosion, and deposition among different treatments, and at different heights above the ground, we used a permutated multivariate analysis of variance (PERMANOVA) procedure with the Primer-PERMANOVA+ package (Anderson *et al.*, 2008). The PERMANOVA procedure permutes a distribution based on an Euclidean distance matrix, and calculates a permutated *F*-statistic and associated *P*-value, similar to a one-way ANOVA, but without any assumptions of normality. The PERMANOVA procedure then allowed us to conduct a number of multiple comparisons to test the differences among different treatments using the *t*-distribution. Analyses were conducted separately for engineering practices, plant practices (with separate analyses under and between solar panels), and for biocrust practices. While we understand that our three measurements of sand transport rate are not true replicates in the sense that they were placed under the same pv solar power station, nevertheless the measurements provided us with reasonable indications of potential differences among the various treatments. Experimental data of wind velocity were processed using Microsoft Excel 2016 and analyzed using a one-way ANOVA with SPSS 19.0 statistical software (SPSS Inc., Chicago, IL, USA). Means comparisons were performed following a significant difference in the mean effects using a protected Tukey’s Honest Significant Difference (P ≤ 0.05). The wind speed profile equation was simulated by Microsoft Excel 2016 and the wind velocity flow field was drawn using Surfer 8.0 (Golden Software, USA).

RESULTS AND DISCUSSION

*Characteristics of the Wind Velocity and the Wind Velocity Flow Field between Solar Panels*

The average wind velocities at the heights of 20- and 200-cm within the peripheral area were 1.51 m/s and 3.64 m/s, respectively, while between the solar panels the average wind velocities were 1.06 m/s and 1.40 m/s, respectively. Wind velocities between the solar panels were reduced 29.8% and 61.5% at the heights of 20 cm and 200 cm when compared with the wind velocities within the peripheral area. Therefore, the arrangement of the solar panels significantly decreased wind velocities. However, due to their arrangement with a wide wind inlet and a narrow wind outlet, the velocity of the wind flowing through the solar panels was decreased at the inlet and increased at the outlet that formed distinct zones of deflation, DSA, and deposition. Figure 5 indicated the wind velocities were significantly higher at location A which resulted in the creation of the DSA zone, while the wind velocities were lower at location B which resulted in the formation of the deposition zone. Thus, it is important to give consideration to the location of the zones of deflation, DSA, and deposition when placing the protective treatments.

*Sand Transport Rates*

The sand transport rates refer to the quantities of sediment transported by the wind per unit of surface area and time. Table 2 shows that the sand transport rate values in all the treatments consistently decreased with increased height, except for some irregular changes, for instance, where there was a reversed trend in treatment E4 when heights were above 15 cm. Compared with the control, all the treatments reduced the total quantities of horizontal sand transport.

Among the engineering practices, the total horizontal sand transport displayed the rank order trend from highest to lowest as E-CK >E1 >E3 >E2 >E4. Compared with the control, the reductions produced by treatments E1, E2, E3, and E4 were 51%, 78%, 74%, and 87%, respectively. The results of PERMANOVA determined there were significant differences among every treatment at various height intervals above the ground surface and along the total horizon distance (F=99.81, P<0.01). The results of multiple comparisons of sand transport rates at different heights showed within the 10-25 cm interval, there were no significant differences between the control treatment and the E1 treatment. While there were no significant differences among treatments E2, E3 and E4 within the 0-10 cm interval, there were significant differences among the E-CK, E1 and other treatments. Within the 0-5 cm interval, there were no significant differences between the E2 and E3 treatments (Table 2). These results indicated that the influence of various engineering treatments on the sand transport rates were primarily concentrated within the 0-10 cm range near the surface. The E4 treatment exerted the greatest reductions in the sand transport rate. Therefore, the E4 treatment exhibited results as the preferred prevention and control practice among the engineering treatments as it had the lowest sand transport rates.

Whether between the solar panels or under the solar panels, the sand transport rate significantly decreased within the total horizon distance for the V1 and V2 treatments (For F values between 146.42 and 12.75, the P<0.01 and for F values less than 12.752, the P<0.05). Under the solar panels, the total horizontal sand transport was compared among the plant treatments and followed the tread, V-CK> V1 >V2 with the reductions resulting for the V1 and V2 treatments being 20% and 36%, respectively, below with the control. Between the solar panels, the total horizontal sand transport followed the trend of V-CK>V2>V1, and decreased by 86% and 78% for the V1 and V2 treatmetns in comparison with the control, respectively. However, different treatments had different effects on the sand transport rates at different heights. Between the solar panels, the sand transport rates of V-CK significantly differed between the V1 and V2 treatments while there were no differences displayed between the V1 and V2 treatments except for the 17.5-20 cm heights (Table 2). Under the solar panels, there were no differences among the three treatments within the 0-10 cm interval, and the differences at other heights were similar to the total sand transport rates. These results indicated that the V1 and V2 treatments had greater impacts on reducing wind erosion between the solar panels areas. Studies have shown that vegetation coverage significantly affects sand transport rates. When the vegetation coverage is relatively dense, the sand transport rates have been shown to be markedly less (Huang *et al.*, 2001; Lv & Dong, 2012; Salahat, 2016; Zhao *et al.*, 2005). In winter and spring, the Mu Us sand-land usually experiences high wind velocities which, combined with the relatively sparse vegetation coverage, typically results in serious wind erosion. In this study, during the early stages of plant growth, the sand transport rates for the V1 and V2 treatments were greater than the control, but decreased with continued plant growth. These results are in agreement with the results reported in previous studies (Li *et al.*, 2007; Zhao *et al.*, 2005).

The sand transport rates associated with the biocrust treatments within the solar panel area gradually decreased the sand transport rates with increased heights (Table 2). The results of the PERMANOVA analysis determined that the biocrust treatments displayed significant differences in sand transport rates within the 0-12.5 cm heights. The total horizontal sand transport rates (F=104.98, P<0.05) displayed no significant differences within the 12.5-25 cm heights and with the previous mentioned results indicated that the influence of biocrust treatments on sand transport rates was primarily concentrated within the 0-12.5 cm height above the surface. Biocrust is a highly complex community of mosses, cyanobacteria, lichens, bacteria, etc, which had initially displayed 12% coverage of the terrestrial surface which is typical in comparison with the results of previous studies (Bu *et al.*, 2013; Rodriguez-Caballero *et al.*, 2018). The biocrust mulch obviously changed the soil surface physical conditions and reduced the direct effects of wind erosion. It has been reported that the exopolysaccharides mainly composed of glucose, mannitol, arabinose and galactose, secreted by biocrust bacteria can aggregate the sand particles which helps reduce the susceptibility of the larger particles to wind erosion (Zhang, 2005). It is thought that similar mechanisms were involved that resulted in the reductions in the sand transport rates. In this study, the coverage of treatment B1 and B2 reached approximately 60% and 70%, respectively, when fully established. The total horizontal sand transport rates observed with the B1 and B2 treatmetns was significantly decreased by 65% and 71%, respectively, when compared with the control. Therefore, both biocrust treatments demonstrated effective reductions in the sand transport rates with slightly better results for the B2 treatment.

All the treatments significantly reduced the sand transport rates within the solar panel area. The largest reductions in the area between the solar panels occurred for the E4 treatment, and under the solar panels the largest reductions were observed for the B2 treatment. The results indicated that the configuration and coverage of the plant treatments significantly affected their sand-fixing capacity (Lv *et al.*, 2014).

*Wind-Sand Flow Structure*

The distribution of sediment within the sand flow along the height of the flow is called the wind-sand flow structure. The relative sand transport rate index is used to describe the wind-sand flow structure, which refers to the percentage of transferred sand quantities within each height interval of the total distribution.

As shown in Fig. 6, the sand transport rates associated with all the treatments gradually decreased with increased height. In Fig. 6A, the sand transport rates observed for treatments E1, E2, and E3 decreased rapidly below 17.5 cm, whereas the rate of decrease was relatively unchanged above 17.5 cm. In Figs. 6B and 6C, the sand transport rates observed for the plant treatments under the solar panels decreased rapidly within the 0-10 cm height range, whereas the rate of decrease was relatively unchanged within the 10–25 cm height range. The sand transport rate observed for the V1 treatment between the solar panels was drastically reduced within the 0-15 cm height range, whereas the rate observed for the V2 treatment showed stable changes within the 0-25 cm height range. In Fig. 6D, the sand transport rates associated with all the treatments decreased drastically within the height range of 0–10 cm, whereas the decrease was relatively constant within the height range of 10–25 cm.

The sand transport rates associated with all the treatments gradually decreased with increased heights, and all the treatments significantly reduced the near-surface sand content. The underlying ground surfaces with their different properties played an important role in the turbulence of the airflow. Where the height above the soil surface was greater than 20 cm, the content of sand particles was generally unchanged.

*Sand Erosion and Deposition*

Fine particles and associated nutrients in soil that has been depleted directly by wind erosion has been shown to be a primary contributor to soil degradation (Yan *et al.*, 2013). Therefore, our opinion is that the hazards caused by erosion has more serious impacts than deposition. In this study, practices that caused deposition were defined as more effective in reducing wind erosion. It was also observed that with smaller values of deposition treatments displayed improved results in the reduction of erosion.

Within the DSA zone, the different engineering treatments had significant differences in the sand erosion-deposit budget (F=1046.6, P<0.001). The sand erosion-deposition budget associated with the engineering treatments indicated that the control treatment displayed erosion losses of 23.8 cm. The erosion value of the E1 treatment was 6.0 cm which was a 75% reduction compared with the control. Treatments E2, E3, and E4 resulted in depositions of 1.0 cm, 1.6 cm, and 3.1 cm, respectively, and the sand erosion-deposit budget decreased by 104%, 107% and 113% in comparison to the control, respectively, and indicated the three treatments provided erosion reduction benefits. Multiple comparisons showed that the there were significant differences among the different engineering treatments, and that the E2 treatment performed better within the DSA area.

Different plant measures also reduced the erosion budget and had significant impacts in the sand erosion-deposit budget within the DSA area (F=211.094, P<0.01). Compared with the control, the sand erosion-deposit budget observed for the V1 and V2 treatments decreased the budget by 65% and 58%, respectively, with slightly better non-significant results observed for the V2 treatment. Further analysis showed there were significant differences between the V-CK and the V1 and V2 treatments, but no significant differences existed between the V1 and V2 treatments (Fig. 7B). Comparing the optimal results of engineering measures and plant measures, it was determined that the E2 treatment was more appropriate for this area because of higher erosion rates observed for V2 treatment.

In the deposition zone associated with the engineering practices, the E1 treatment resulted in the most serious deflation in comparison to the control. In contrast, all the remaining engineering treatments produced deposition with the lowest values observed for the E4 treatment (Fig. 7A). Studies have shown that the size and layout of checkerboard sand barriers significantly affects the erosion control effects (Tian *et al*., 2015). In the present study, the wheat straw checkerboard sand barriers resulted in severe wind erosion, possibly due to the insertion of the chain pins into the bottom of the internal concave surface. After multiple comparisons, there were significant differences between E1, E2 and other treatments, but no significant differences between the E3 and E4 treatments. Thus, treatments E3 and E4 performed better within the deposition zone when compared with the other engineering treatments.

In terms of plant practices within the deposition zone, the differences among the three treatments were significant (Fig. 7B). The results of the treatments had some unexpected results when compared with our initial expectations. The control treatment resulted in gravel deposition, while the V1 and V2 treatments resulted in 2.5 cm and 2.0 cm of gravel erosion, respectively. Plausible reasons for this phenomenon may be as follows: (1) the plants grown under the solar panels and within the DSA zone played an important role in controlling and resisting wind erosion, which decreased the amounts of the sand erosion-deposition budgets; and/or (2) the plant intervention destroyed the structure and integrity of the original landforms within the deposition zone, which made the surface more vulnerable to erosion and increased the amounts of the sand erosion-deposit budgets.

Under the solar panels, the quantities of the sand erosion deposition budget under the plant treatments were significantly less than those quantities measured between the panels. In comparison to the budget values within the DSA zone, the sand erosion deposition budget under the solar panels values for the V1 and V2 treatments were reduced by 57% and 54% , respectively, and when these same treatments were compared within the deposition zone, the sand erosion deposition budget were reduced by 44% and 11%, respectively. The V1 and V2 treatments still allowed erosion to occur, but reduced the quantities of erosion by 40% and 22% compared to the control, respectively, but displayed no significant differences between the V1 and V2 treatments. Where the plant cover is less than 20%, it has been observed that the rate of wind erosion is significantly greater (Bu *et al.*, 2015a; Zhao *et al.*, 2005)*.* In the present study, we observed that the sand erosion deposit budgets were slightly decreased or increased where the plant cover was less 10%. The sand erosion deposit budgets produced by the plant treatments increased to various degrees, which was related to the configuration and coverage of the plant treatments.

The B1 and B2 biocrust treatments had sand deposition under the solar panels for both treatments, while the control exhibited serious erosion. Compared with the control, the sand erosion-deposition budgets associated for the B1 and B2 treatments decreased by 109% and 114%, respectively, and there were no significant differences between B1 and B2 treatments (Fig. 7C). Moss and lichen crusts have been shown to have high resistance to wind erosion damage, but it has shown that algal crust may facilitate or cause wind erosion damage (Bu *et al.*, 2015a; Wang *et al.*, 2004). In the present study, the algal crusts were easily broken which resulted in reduced surface coverage and increased wind erosion. The effects of the moss crust to resist wind erosion were better than the algae crusts, possibly because the moss crust surface coverage reached 70% late in the study, and provided partial stabilization for the sand. Therefore, it was concluded that the B2 treatment would be more appropriate for use within this area.

All the treatments significantly reduced the sand erosion-deposition budget, but the adaptable area was different for the different treatments. Under the solar panels, the best treatment for resisting wind erosion damage was the B2 treatment. Within the DSA zone, the most suitable treatments were the E2 treatment, while the E3 or E4 treatments should be chosen for placement within the deposition zone. The material of the E2 treatment was same as the E4 treatment within the DSA area, that is to say the best treatment for placement between the solar panels was the E4 treatment.

*Wind Velocity Profile*

The wind velocity profile refers to the distribution of the wind velocity along with the height above the soil surface and is closely related to the intensity of the wind turbulence. Within the solar panel area, the wind velocity observed above the engineering treatments generally increased with height (Fig. 8). This pattern was consistent with the wind characteristics of the atmospheric surface layer and with the results reported by Wu *et al*. (2013). The range of wind velocities observed above the bare check treatment and the E2 treatment were relatively dispersed while the wind velocities above the other engineering treatments were relatively concentrated and regular. The wind velocity observed for the E1 treatment increased rapidly within the 20-40 cm height interval and decreased within the 60-80 cm height interval. The wind velocity observed above the E4 treatment increased slowly compared with the control. Downtrends were observed above the E3 treatment within the 20-40 cm height interval and above the E4 treatment within the 80-100 cm height interval. The average wind velocity distribution with height indicated that compared with the control, the other engineering treatments effectively reduced the wind speed (Fig. 8A). The greatest reductions of the wind velocity was observed above the E1 treatment at a height of 20 cm, and above the E3 treatment for the remaining heights. There were significant differences among the E-CK treatment when compared with the E1 and E2 treatments at every height, while the differences in means comparisons between the E3 and E4 treatments were not significant (Supplement. Table 1). Within the entire height profile, the wind velocities observed for the E-CK, E1, and E2 treatments varied within the ranges of 4.5-7.0, 2.0-4.5, 4.5-6.0 m/s, respectively, and the wind velocities for the E3 and E4 treatments were varied within the ranges of 2-3 m/s. The wind velocity observed above the E3 treatment had the most significant reductions in comparison with the control and the changes in wind velocity was relatively constant indicating improved stabilization of the sand on the ground surface.

The wind velocities associated above the plant treatments increased gradually with height above the soil surface. The range of wind velocities was also relatively concentrated above the control treatment and was relatively dispersed above the V1 treatment (Fig. 9). Above the V1 treatment, the wind velocity increased rapidly within the height range of 20–40 cm and then increased slowly within the height range of 40–200 cm. Within the 20-200 cm height intervals, the wind velocity generally varied within the range of 1–6 m/s, although the overall changes were relatively constant. Above the V2 treatment, the wind velocity gradually increased throughout the entire height range, but the changes between the adjacent height intervals were apparently random. The average wind velocities within the 0 to 20-cm height interval followed the trend of V-CK > V1 > V2 while the effectiveness of the plant treatments for the other height intervals followed the trend of V1> V-CK > V2 (Fig. 9A). The results of the one-way ANOVA analysis showed that plant treatments had no significant effects on wind velocities at different height intervals with the exception of the 40-60 cm height intervals where differences in statistical significance were observed (F=2.007, P>0.05).

The plant treatments consistently reduced the wind velocities within the lower 20-cm interval and had different effects on the velocities within the upper intervals, but the overall result was that the wind profile was affected by the plant treatments. Plant morphology has been shown to significantly affect the erosion control characteristics of vegetation (Hong *et al.*, 2016; Zhang *et al.*, 2016b). *Sedum aizoon* L. is a dicotyledon with hard stems. The stems bend less in the wind and, thereby, reductions in the wind velocitiestypically result. This species can effectively reduce surface wind velocities within the 0 to 20-cm height interval and strongly influences wind velocities within the upper intervals. *Pennisetum alopecuroides* (L.) Spreng*.* is a monocotyledon that is susceptible to the effects of wind and is characterized by soft stems with long and slender leaves. *Pennisetum alopecuroides* (L.) Spreng*.* was easily bent and helps to protect the plant from the damage of wind erosion. Moreover, compared with *Sedum aizoon* L. which was orderly arranged during transplantation, the random arrangement of *Pennisetum alopecuroides* (L.) Spreng*.* was broadcast planted and exhibited more influence on the wind velocities.

The wind velocities associated with the biocrust treatments gradually increased with the height above the soil surface and was similar to the results observed for the engineering treatments. The changes within the wind profiles associated with the plant treatments were generally random, which may have been related to the properties of the underlying surface (Lü & Dong, 2006).

All three biocrust treatments reduced the near-surface wind velocity and played a role in erosion control. The red clay mulch, *Pennisetum alopecuroides* (L.) Spreng*.*, and the moss crusts were both shown to be effective in providing the desired impacts on the wind velocities.

*Aerodynamic Roughness (z0)*

Aerodynamic roughness (z0) is an index of the effects of the ground surface on the airflow and usually represents a geometric height of zero wind velocity. Figures 8A and 9A display the average wind velocities variations with increased height under the engineering treatments and plant treatments within the solar panel area. It can be seen that the wind velocities increased gradually with height, which conforms to the logarithmic distribution law (Zhang *et al*., 2016a). Table 3 shows the fitting results of a logarithmic function of the wind profiles and the z0 calculation results. The fitting coefficients all exceeded 0.8 and indicated the fitting results were reliable. The roughness under the engineering treatments followed the trend of E1 > E3 > E-CK = E4 >E2. Compared to the control, the roughness can be divided into three categories: increased, decreased, and neutral. The roughness of the E1 and E3 treatments were 0.748 cm and 0.163 cm, respectively, which were 9.6 times and 2.1 times greater than the bare land, respectively. The roughness under the E2 treatment was reduced by an order of magnitude in comparison to the control and may be considered as approximately 0 cm. The reason for the increased roughness above the E1 treatment was attributed to the arrangement of the wheat straw checkerboard. We knew that the wheat straw checkerboard was 10 cm vertically into the ground (Fig. 3b), and this insertion made the near-surface more uneven and increased the roughness, which reduced the wind speed near the surface. This observation is consistent with the results in Fig.8A that the wind speed at the height of 20 cm above the E1 treatment exhibited the lowest values among all the treatments. The reason for the roughness increase above the E3 treatment may be related to the wind erosion characteristics of the soil. Studies have been shown that when the soil surface particle fraction was <0.125 mm, the soil surface was susceptible to wind erosion (Yan *et al.*, 2013). Though red clay is characterized by the strong bond between the soil particles, the fine particles within the surface layer were still removed by wind erosion. Over time this process resulted in surface soil particles coarsening and further resulted in slightly increased surface roughness. The reason for the decreased roughness within the E2 treatment may be as follows: because of various sizes and shapes, there was no smooth transition among the gravel and an extremely uneven surface layer was created that accelerated the air flow near the surface. However, because of high surface coverage, the gravel mulch displayed an improved efficiency in the reduction of wind erosion in comparison to the results observed for bare land.

The V1 and V2 treatments both increased the roughness and followed the trend of V2 > V1 > V-CK (Table 3). Compared with the control, the V1 treatment increased the roughness by 6.6% while the V2 treatment increased the roughness by 30.3%, which indicated that the V2 treatment had a greater effect on wind speed near the surface (Supplement Table 1). The wind velocity above the V2 treatment exhibited the lowest values in comparison to all the other plant treatments. Zhao *et al*. (2007) indicated that the quantities of plant cover and surface roughness were positively correlated and these two properties were negatively correlated with soil wind erosion. It has also been reported when the coverage of natural vegetation reached 60% that soil wind erosion was effectively prevented (Meng *et al*., 2018). However, in this study, all of the plant coverages were less than 10% because of the harsh ecological environment. Therefore, when vegetative practices are implemented in similar areas, a combination of factors should be considered when evaluating the effectiveness for soil wind erosion reductions.

The wind erosion resistance exhibited by biocrusts is closely related to the crust development stage and the type and nature of surface conditions (Bu *et al.*, 2015b; Li & Shen, 2006). The erosion control mechanism of biocrusts is generally similar to the behavior displayed by gravel mulch such that the aerodynamic roughness has been increased and the near-surface wind velocity flow field has been altered. Therefore, the necessary wind velocity threshold for moving surface sand particles has been increased and reductions in wind erosion have been the subsequent result.

CONCLUSIONS

The hazards caused by wind erosion within a sandy area of northwest China were aggravated due to the construction of a photovoltaic power station. In a comparison to the periphery area, the solar panels significantly reduced the wind velocities, however, due to the arrangement of the solar panels with a wide wind inlet and a narrow wind outlet, the wind velocities through the solar panels were reduced at the inlet and increased at the outlet. These changes in the wind velocity flow field caused the formation of serious erosion zones and deposition zones within the localized area. The resulting changes in patterns of erosion and deposition destroyed the original soil structure and increased the difficulties of natural vegetation restoration. These changes not only increased the local land degradation potential, but also resulted in some security issues and increased the maintenance costs for the photovoltaic power station. Therefore, it’s necessary and expediate to identify appropriate wind erosion control practices to reduce erosion and prevent potential land degradation.

In the study area, deflation zones, direct shear abrasion (DSA) zones, and deposition zones were identified that had been created by the added presence of the photovoltaic power station. Deflation zones were located under the solar panels and resulted in slight wind erosion on the surface layer. The DSA zones were located at the base of the solar panels where the redirection of the prevailing winds has caused the formation of a V trench that is typically 1 meter wide and 1 meter deep at the outlet. The downward directed wind from the rear of the solar panel intersects the soil at the front of the solar panel and the shearing effects of the wind caused a V trench to be formed. Deposition zones were located between the solar panels and are typically a stripped region 6 meters wide and 40 centimeters thick which formed between the outer edge of the DSA zone and the deflation zone under the next row of solar panels. To address the serious DSA and deposition occurring between the solar panels, we evaluated various control treatments that included engineering, plant, and biocrust treatments.

Engineering, plant, and biocrust treatments effectively reduced wind erosion, but the optimal practices were found to be different within the different zones. Between the solar panels, the E4 treatment was more appropriate which resulted in approximately a 87% reduction in the total sand transport rate, that is to say the gravel mulch and the red clay mulch were the most appropriate erosion control practices within the DSA zones and the deposition zones, respectively. Under the solar panels, it was found a more appropriate practice was to implement a biocrust practice consisting of a moss biocrust. This biocrust decreased the sand erosion-deposit budget and sand transport rate by 114% and 71%, respectively. Therefore, for the minimization of wind erosion hazards at the PV power stations and similar projects within the sandy areas of northwest China, we recommend the establishment of moss crust under the solar panels, as well as implementation of a gravel mulch and red clay mulch within the DSA zones and the deposition zones, respectively. We feel the implementation of these recommended practices will greatly reduce the severe soil wind erosion and land degradation that is rapidly occurring at the PV power station locations and help stabilize the fragile ecosystems.

Sustainable development of ecological environments is an inevitable choice for human society in the future, and as more clean energy enterprises will be established, such as photovoltaic power stations. However, different regions have different environmental conditions, climatic features, geological conditions, and erosional characteristics; therefore, the selection of the most effective appropriate practices to reduce erosion and help protect the ecosystems will also be different. There is a need that relevant research be conducted to address these issues and to help protect our existing environment from the increased threat of land degradation.

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Figure Captions

**Figure 1**. A schematic side view showing the distances, placement of the solar panels, and locations of the deposition, direct shear abrasion (DSA), and deflation zones. Photographs showing the deposition, DSA, and deflations zones relative to the solar panel placement.

**Figure 2**. A schematic showing an aerial view of the different treatments within the experimental area including the deposition, direct shear abrasion (DSA), and deflation zones. Please note that the abbreviations refer to the treatments which are E-CK-bare land control, E1-wheat straw checkerboard, E2-gravel mulch, E3-red clay mulch, E4-DSA (Direct Shear Abrasion) + gravel /deposition zone + red clay measure; V-CK-natural vegetation restoration area, U-V1 & B-V1-*Sedum aizoon* L. planting area under the solar panel and between the solar panel, respectively; U-V2 & B-V2-*Pennisetum alopecuroides* (L.) Spreng. planting area under the solar panel and between the solar panel, respectively; B-CK-natural vegetation restoration, B1- algal crust mulch, and B2- moss crust mulch.

**Figure 3**. Photographs showing the soil surface conditions of all the treatments in relation to the placement of the solar panels. Please note that the abbreviations refer to the treatments which are E-CK-bare land control, E1-wheat straw checkerboard, E2-gravel mulch, E3-red clay mulch, E4-DSA (Direct Shear Abrasion) + gravel /deposition zone + red clay measure; V-CK-natural vegetation restoration area, V1-*Sedum aizoon* L. planting area, V2-*Pennisetum alopecuroides* (L.) Spreng. planting area, B-CK-natural vegetation restoration, B1- algal crust mulch, and B2- moss crust mulch.

**Figure 4**. Schematic showing a side view of the instrumentation placement and photographs of the instruments and their placement in the regards to the solar panels.

**Figure 5**. Diagram of the wind velocity flow field in regards to the side view of a solar panel placement where the wind velocity flow lines are shown for the inlet and outlet areas of the solar panel and are shown for approximately a 9-m distance and a 2-m height above the soil surface.

**Figure 6**. The relative sand transport rate versus distance above the soil surface for the engineering, plant, and biocrust practices where the treatments are E-CK-bare land control, E1-wheat straw checkerboard, E2-gravel mulch, E3-red clay mulch, E4-DSA (Direct Shear Abrasion) + gravel /deposition zone + red clay measure; V-CK-natural vegetation restoration area, V1-*Sedum aizoon* L. planting area, V2-*Pennisetum alopecuroides* (L.) Spreng. planting area, B-CK-natural vegetation restoration, B1- algal crust mulch, and B2- moss crust mulch.

**Figure 7**. The sand erosion-deposit budget associated with the engineering, plant, and biocrust treatments where the treatments are E-CK-bare land control, E1-wheat straw checkerboard, E2-gravel mulch, E3-red clay mulch, E4-DSA (Direct Shear Abrasion) + gravel /deposition zone + red clay measure; V-CK-natural vegetation restoration area, V1-*Sedum aizoon* L. planting area, V2-*Pennisetum alopecuroides* (L.) Spreng. planting area, B-CK-natural vegetation restoration, B1- algal crust mulch, and B2- moss crust mulch.

**Figure 8.** The changes in wind velocity with height above the soil surface for the engineering treatments where the treatments are E-CK-bare land control, E1-wheat straw checkerboard, E2-gravel mulch, E3-red clay mulch, and E4-DSA (Direct Shear Abrasion) + gravel /deposition zone + red clay measure.

**Figure 9.** The changes in wind velocity with height above the soil surface for the plant treatments where the treatments are V-CK-natural vegetation restoration area, V1-*Sedum aizoon* L. planting area, and V2-*Pennisetum alopecuroides* (L.) Spreng. planting area.

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