THE FACTORS AFFECTING WIND EROSION IN SOUTHERN UTAH

by

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of

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in

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ABSTRACT

The Factors Affecting Wind Erosion in Southern Utah

by

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Wind erosion and dust transport continue to increase in many parts of the world, leading to decreased soil quality, respiratory diseases, traffic accidents, and accelerated snow melt. The processes that control sediment flux at small scales of mm to m are well understood, but the processes that control sediment flux at larger scales of km to hundreds of km are less well understood. Here, we use 9 years of data from a network of 52 sediment collectors and a machine-learning model to describe the factors that determine horizontal sediment flux over a roughly 6270 km^2 area in southern Utah and western Colorado, USA. Previous-reported regression tree analyses of the first 5 years of data (soils, vegetation, and weather information) explained 56% of the variation in sediment flux, and wind speed was the most important variable. Regression tree analysis of the same dataset improved the variance explained to 64%. Including simulated estimates of soil moisture further improved the variance explained to 69%. Finally, including four years of additional sediment collection data further improved variance explained to 81%. Thus, through several incremental changes, this research improved our ability to explain variance in sediment flux from 56 to 81% variance explained. In this most complete analysis, variable importance decreased from wind speed > seasonal rain > soil moisture > sand content. Because additional field-collected data provided the greatest increase in variance explained, our results highlight the importance of developing spatially and temporally extensive datasets to improve understanding and management of sediment flux in semi-arid systems. An important product of this research is a quantitative model that can be used to estimate sediment flux under various climate or land use conditions.

(58 pages)

PUBLIC ABSTRACT

The Factors Affecting Wind Erosion in Southern Utah

Mehmet Ozturk

Wind erosion is a global issue and affecting millions of people in drylands by causing environmental issues (acceleration of snow melting), public health concerns (respiratory diseases), and socioeconomic problems (costs of damages and cleaning public properties after dust storms). Disturbances in drylands can be irreversible, thus leading to natural disasters such as the 1930s Dust Bowl. With increasing attention on aeolian studies, many studies have been conducted using ground-based measurements or wind tunnel studies. Ground-based measurements are important for validating model predictions and testing the effect and interactions of different factors known to affect wind erosion. Here, a machine-learning model (random forest) was used to describe sediment flux as a function of wind speed, soil moisture, precipitation, soil roughness, soil crusts, and soil texture. Model performance was compared to previous results before analyzing four new years of sediment flux data and including estimates of soil moisture to the model. The random forest model provided a better result than a regression tree with a higher variance explained (7.5% improvement). With additional soil moisture data, the model performance increased by 13.13%. With full dataset, the model provided an increase of 30.50% in total performance compared to the previous study. This research was one of the rare studies which represented a large-scale network of BSNEs and a long time series of data to quantify seasonal sediment flux under different soil covers in southern Utah. The results will also be helpful to the managers for controlling the effects

on wind erosion, scientists to choose variables for further modeling or local people to increase the public awareness about the effects of wind erosion.

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INTRODUCTION

Desertification affects 250 million people in the developing world via the loss of soil nutrients and a decrease in soil productivity, and could potentially impact 2.5 billion people globally (Okin et al., 2009; Reynolds et al., 2007). Wind erosion is an important component of desertification (Li et al., 2007; Castillo-Escrivà et al., 2019; Yang & Leys, 2014). Sediment transported by wind erosion is associated with decreases in land/soil quality by removing organic matter in the topsoil (Saha, 2003), decreases in visibility leading to traffic accidents, changes in snow chemistry (Rhoades et al., 2010; Li et al., 2013), decreases in snow packs and consequently in water supplies (Li et al., 2013; Painter et al., 2007; Clow et al., 2016). It is also a public health concern since the particles transported by wind can cause respiratory problems and diseases due to windborne viruses (“Mining Topic”, 2018).

Aeolian research studies, designed to understand the factors that determine wind erosion and inform land management have been performed for nearly a century (Bagnold, 1941; Jickells et al., 2005; Webb & Strong, 2011). At small scales of mm to meters, the mechanisms of wind erosion are fairly well understood (Zobeck et al., 2003; Shao, 2008). Broadly, wind erosion can be described as a balance of forces that remove particles from the surface (i.e., aerodynamic forces such as wind speed), and forces that oppose particle removal (e.g., soil moisture, soil texture, soil roughness, soil crusts, etc.) (Shao, 2008). Wind speed is an important aerodynamic force, and surface roughness, soil moisture, vegetation, soil texture, and soil crust are important for preventing wind erosion. For example, soil moisture allows capillary forces to develop between soil grains, thus preventing wind erosion (Chen et al., 1996; Bergametti et al., 2016) while vegetation can provide substantial protection against wind erosion by extracting momentum from the flow and reducing the shear stress acting at the surface (Crawley et al., 2003; Marshall, 1971; Wolfe et al., 1993). Therefore, it is thought that horizontal dust mass will be a function of vegetation types, soil crusts (biological and physical crust), soil aggregates, land-use history, soil type, surface roughness, wind speed, and soil moisture (Zobeck, 1991; Webb & Strong, 2011; Breuninger et al.,1989).

Despite wind erosion's significance and a good understanding of small-scale factors affecting wind erosion, there is a recognized gap in knowledge of the factors that determine wind erosion at larger spatial scales of km to hundreds of km (Webb et al., 2006; Webb & Strong, 2011). A primary problem for understanding large-scale dust emission is that large-scale measurements of ground-level sediment flux that are needed to develop and validate models of dust emission are generally lacking (Webb & Pierre, 2018; Xi & Sokolik, 2015; Shao, 2008). Further, because many factors interact to affect sediment flux, it is difficult to measure sediment flux under all potential combinations of factors that determine sediment flux (Bryan et al., 1989; Shao, 2008; Webb & Strong., 2011; Gillette, 1979). As a result, there remains a need for spatially and temporally extensive sediment flux measurements to improve and validate our understanding of the factors that determine sediment flux.

Most field studies to date have individually focused on a factor or a few factors that accelerate and prevent wind erosion. However, many of the factors controlling wind erosion are related to each other and should be considered together (Webb & Strong, 2011; Zobeck, 1991). For example, soil organic matter facilitates water infiltration, increases water-holding capacity, and improves aggregate stability while the amount of soil organic matter can depend on vegetation cover (Franzluebbers, 2002). Therefore, modeling approaches that can incorporate correlated data streams are needed. Only a few studies have been done to observe and quantify ground-level wind erosion over large areas (Flagg et al., 2013; Nauman et al., 2018). Nauman et al. (2018) investigated the impact of various land uses and climate on aeolian sediment flux and reported that sediment flux was very high in grazed locations, and climate variables such as precipitation, temperature, and wind played an important role on the amount of the sediment transported. On the other hand, Flagg et al. (2013) did examine large-scale factors determining sediment transport and found that wind speed was the most important factor determining sediment flux at large spatial scales under different vegetation, soil covers, and land-uses. Although Flagg et al. (2013) found that seasonal precipitation was a poor predictor of sediment transport, it is likely that more detailed information about soil moisture would be important to sediment transport since it has a direct impact on wind erosion threshold (Chen et al., 1996; Bergametti et al., 2016; Chepil, 1956; Hotta et al.,1984; Shao, 2008).

Here we tested three approaches to improve the understanding of the variation in sediment flux using the same network of sediment flux collectors reported by Flagg et al. (2013). First, we used a random forest model to describe sediment flux. The random forest has been shown to improve upon the type of regression tree analyses used by Flagg et al. (2013) (Brieuc et al., 2018; Cutler et al., 2007). Next, we simulated soil moisture over time at the locations of 10 sediment collectors using the Hydrus 1D soil water movement model. Finally, we tested model improvement with four years of new data because we anticipated that it would require a large amount of data to effectively describe a large number of interactions that can occur among many different varying parameters.

LITERATURE REVIEW

Desertification is threatening human-beings in arid and semi-arid areas (UNEP, 2016), and it became well-known after it thought humanity hard lessons with 1930's Dust Bowls (Field et al., 2009; Shao, 2008; Ravi et al., 2011) and Sahel droughts in the late 1960s and early 1970s (Shao, 2008; Vogt et al., 2011). Wind erosion is a process of wind-forced movement of soil particles and, as a main character of desertification, played a significant role in these phenomena (Shao, 2008). The essential reasons that created profound disturbances to the natural environment can be categorized into anthropogenic and natural causes (Fig. 1). In most cases, it is difficult to assign the disturbances leading to dust emission or wind erosion to human-made or as they could be caused by either (Gillette, 1979). However, enhancing disturbances will boost the adverse impacts of wind erosion directly or indirectly (Kok et al., 2012; Shao, 2008) by removing soil nutrients and organic matter (Flagg et al., 2013; Breshears et al., 2009; Li et al., 2007; Lancaster, 2009; Borrelli et al., 2015), impacting air quality (Monks et al., 2009; Saxton 1995), atmospheric radiation (Tegen et al., 1996), and human health that causes respiratory problems("Mining Topic", 2018).

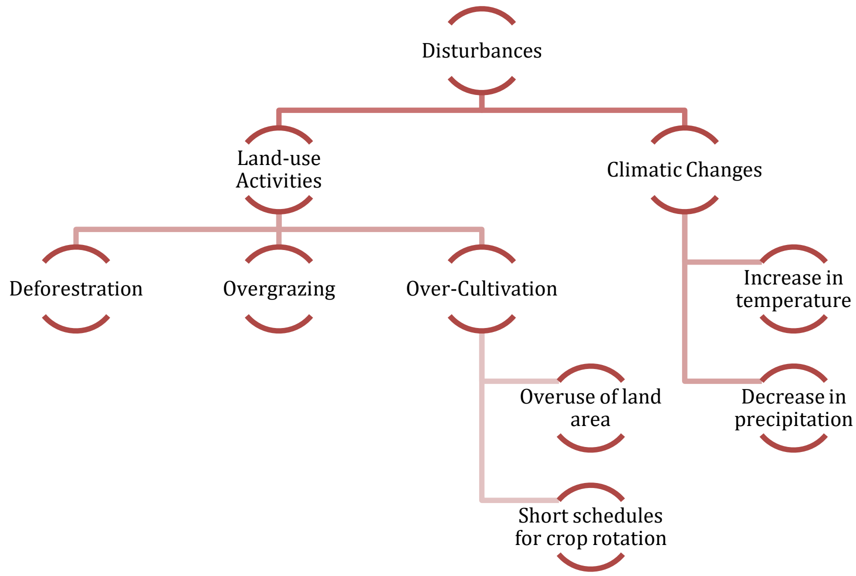

Figure 1 The causes of intense disturbances to natural environments can be human-induced or natural.

The early works of Bagnold (1941) on aeolian processes provided useful information for future studies, and later, many other researchers such as Shao (2008) put more works and supplied more information to increase the understanding of aeolian processes. These processes include wind erosion, transportation, and deposition of sediment by wind (Nickling & Neuman, 2009; Ravi et al., 2011; Lancaster, 2009; Belnap et al., 2011) and occur in different environments from agricultural fields to hot deserts (Lancaster, 2009). Common features among these environments are sparse of vegetation, a supply of fine sediments, and powerful winds (Lancaster, 2009). Furthermore, systems in these environments have a limited amount of water availability: low enough to restrict vegetation cover, resulting in a high proportion of bare grounds on topsoil exposed to wind (Belnap et al., 2011).

Movement of soil particles by the wind in these environments takes places in three different modes (Fig. 2): creep, saltation, and suspension (Bagnold, 1941; Bertici et al., 2014; Nickling & Neuman, 2009). Soil grain motion can be classified based on soil particle size; sand-sized particles are generally transported by saltation and creep while small particles such as clay and silt by suspension (Ravi et al., 2011). Aeolian sediment flux was defined as a horizontal mass flux (Q) and vertical dust flux (F_a) in the previous studies. Horizontal mass flux has an impact on local vegetation and soil distribution with saltating and creeping particles within the ecosystem (Larney et al., 1998; Li et al., 2007) while vertical dust flux is a long-distance transport by suspension (Shao et al., 1993; Li et al., 2007; Shao, 2008).

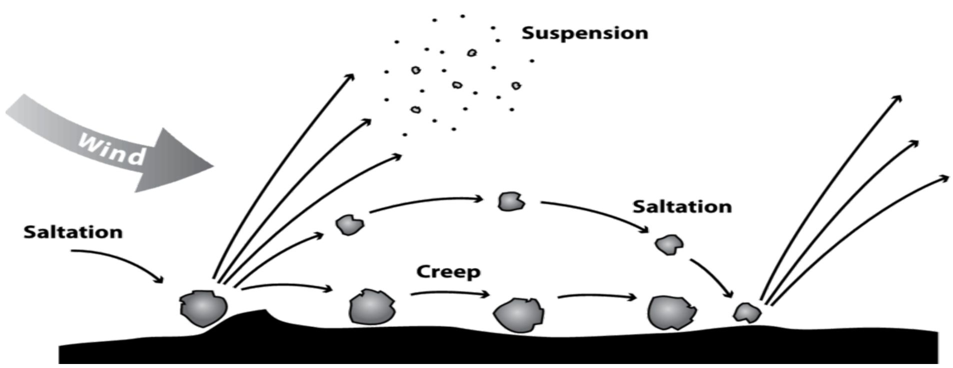

Figure 2 Soil particle movements by saltation, creeping, and suspension (John and Deann, 2009). Large particles will be transported by saltation and creep while small particles by the suspension.

The association between vertical dust emission and horizontal mass flux is assumed to be primarily related (Breshears et al., 2009; Bagnold, 1941; Whicker et al., 2006). Whicker et al. (2014) carried out a study to explore mathematical and empirical approaches for quantifying vertical flux from the horizontal flux and concluded that vertical dust is proportional to horizontal flux. However, it is also pointed out that the punished ratios span several orders of magnitude (Whicker et al., 2014). It is still unclear why the ratio between Q and F_a change so much and it is required to additional measurements such as soil texture, moisture, surface crust, and vegetation cover to obtain more insights (Whicker et al., 2014). In another example, dust produced for the same location was estimated differently by Tegen et al. (2006) and Todd et al. (2007), the reason was the mistakes in the estimations and assumptions of data (Chappell et al., 2008; Tegen et al., 2006). Uncertainty in magnitude of dust emission estimates is still considerable (Webb & Pierre, 2018; Xi & Sokolik, 2015), and field measurements of aeolian sediment transport remain crucial to resolving this issue (Webb & Pierre, 2018) because field measurements are important for understanding wind erosion processes and for evaluating wind erosion models (Shao, 2008). In the past, the problem with field measurements is that they were not adequate in the capacity for testing wind erosion models (Chappell et al., 2003; Shao, 2008). Therefore, monitoring programs must have a good design with enough samplers and other equipment (Table 1) to support analysis and models to understand drivers and effects of wind erosion (Shao, 2008; Webb & Pierre, 2018). These ground-based stations are important to measure factors affecting wind erosion since the balance between friction velocity (u_*), a measure of wind shear at the surface, and threshold friction velocity (u_{*t},) which defines the minimum friction velocity required for wind erosion to occur will depend on the interactions of these factors as Shao (2008) mentioned.

Table 1 A list of parameters should be measured in field experiments (Shao, 2008) to evaluate wind erosion models.

Measurements	**Purposes**
Saltation flux & particle size	Sand drift & saltation models
Dust concentration & particle size	Dust concentration, emission & deposition
Wind speed	Friction velocity, roughness length, land-surface model
Wind direction	Weather
Air temp., humidity & pressure	Weather, land-surface model
Solar radiation	Weather, land-surface model
Precipitation	Weather, land-surface model, crust
Soil Moisture	Threshold friction velocity, crust
Frontal-area index	Threshold friction velocity, roughness length
Fraction of cover	Erodible area, saltation & dust models
Soil particle size distribution	Threshold friction velocity, saltation & dust models

Sediment Sampler

Big Spring Number Eight (BSNE) is commonly used to measure the material transported by wind at different levels above the soil surface (Goossens, 2000). The advantages of BSNE are; it is robust and can collect large amount of sediments, and it can efficiently collect a very wide range of particle sizes (Goossens, 2000). The calibration of BSNE has been done in wind tunnel studies (Fryrear, 1986; Shao et al., 1993; Funk et al., 2004), it is used for catching sediment to calculate the total mass transport related to soil losses by wind erosion (Mendez et al., 2011).

Vegetation

There are many factors affecting wind erosion, and vegetation (cover, structure, and distribution) is thought to be one of the most critical factors because vegetation can provide substantial protection against wind erosion by extracting momentum from the flow and reducing the shear stress acting at the surface (Crawley et al., 2003; Marshall, 1971; Wolfe et al., 1993). Furthermore, Li et al. (2007) found that as lateral cover, a function of plant number density and vertical dimension, declines below 9%, wind erosion increases dramatically. Disturbances cause the vegetation shifts in drylands from grasses to shrubs resulted from overgrazing, agriculture, droughts, and intensity and frequency of fires (Field et al., 2012; Li et al., 2007; Ravi et al., 2007; Shao, 2008). These shifts result in the formation of shrub islands (Island of Fertility) where soil nutrients are progressively confined to zones of litter accumulations beneath canopy covers while bare grounds become nutrient-poor (Field et al., 2012; Li et al., 2007; Ravi et al., 2007). Size, shape and spatial distribution of bare grounds between canopies in drylands resulted from the shifts will determine the susceptibility level to wind erosion (Aguiar & Sala, 1999; Okin et al., 2009) and will lead to a significant increase in aeolian activity (Li et al., 2007; Tchakerian, 2014).

Soil Moisture

The distribution of vegetation and resources in the drylands will determine the soil infiltration capacity, runoff, and soil erosion rates (Puigdefábregas, 2005; Ravi et al., 2007). Wetter surfaces will support vegetation establishment, while vegetation growth will be difficult in drier soils (Ravi et al., 2007). Also, soil moisture will influence the effect of wind erosion as wetter soils prone to be more cohesive and hence have higher erosion thresholds (Cornelis et al., 2004; McTainsh et al., 1998; Ravi & D'Odorico, 2005). Surface soil moisture is exceptionally significant for controlling entrainment and transport of sediment (Lancaster & Nickling, 1994; Nickling & Neuman, 2009). It contributes markedly to the binding forces that stick the particles together through adhesion and capillary effects (McKenna-Neuman & Nickling, 2010).

Wind Speed

The relationship between wind speed and the aeolian sediment movement has long been known (Bagnold, 1941). The erosion processes occur when the wind speed exceeds the minimum value of threshold velocity (Ravi & D'Odorico, 2005; Shao, 2008). The monthly change of wind erosion mostly illustrates a maximum in the spring season, when wind speed is at a maximum and surface protection by vegetation is at a minimum (Shao, 2008).

Soil Texture

Threshold friction velocity (u_{*t}) is related to a range of surface properties, such as soil texture, soil moisture, and vegetation, so the physical properties of soil particles (shape, size, and density) play a significant role in the processes of particle entrainment, transport, and deposition(Shao, 2008). Soil particles are classified into four categories as gravel (2,000 μm < $d \leq 2$ m), sand ($63 < d \leq 2{,}000$ μm), silt ($4 < d \leq 63$ μm) and clay ($d < 4$ μm) (Shao, 2008). Soil texture is an inherent soil property that changes very slowly with time. The soil texture classification used by the U.S. Department of Agriculture is shown in (Fig. 3), and this classification is widely used. In general, coarse soils such as sands are more erodible than finer-textured soils such as clay loam soils since soils with a high clay content normally exist as soil aggregates(Shao, 2008). Soil aggregation is more resistant to wind erosion as particles are physically bound together by plant roots, soil organic matter, and micro-organisms (Barthès & Roose, 2002; Herrick et al., 2005; Rabot et al., 2018). Also, the amount of water which can be absorbed into the soil is the function of clay content.

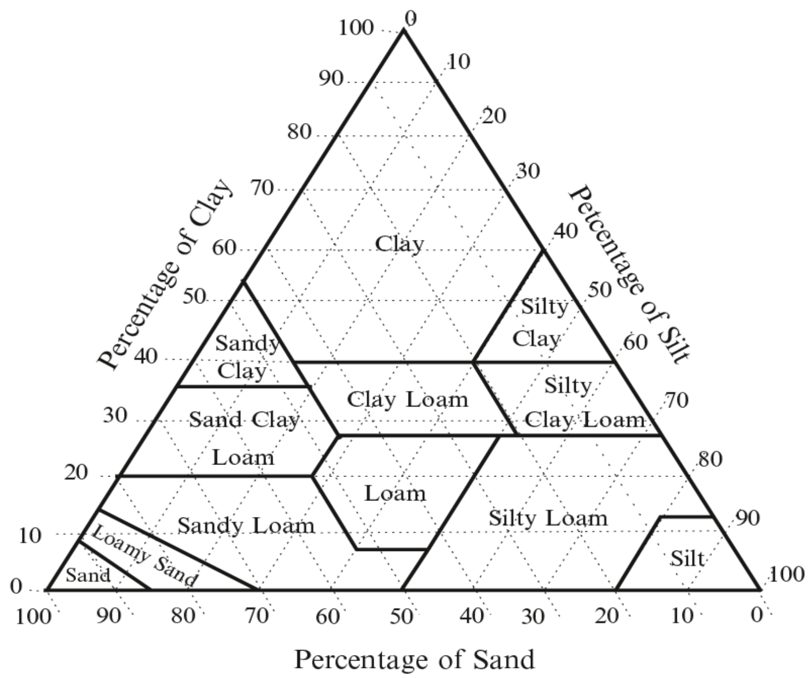

Figure 3 Types of soil texture based on the percentages of sand, silt, and clay by the United State Department of Agriculture.

Soil Crusts

Sediment transportation from soil surfaces depends on the force of wind needed to detach particles from soil surfaces (Belnap & Gillette, 1997), which was defined as threshold friction velocity (Shao, 2008). The existence of physical and biological soil crusts changes many features of the soil surface and thereby play a crucial role in the drylands to protect the surface from the force of the wind (Belnap et al., 2001; Greene et al., 1993). The physical crust can be created by the impacts of raindrops, animal trampling, vehicular traffic and they can form almost any texture except coarse sandy soils that include very low silt and clay (Belnap et al., 2001; Lemos & Lutz, 2010). Physical crusts are protective against wind erosion in bare grounds of arid and semi-arid areas, where precipitation and vegetation cover are low, and the temperature is high. Unlike physical crusts, soil surface roughened by biological crusts can increase infiltration, decrease water runoff, and hold organic matter(Belnap et al., 2001; Belnap et al., 2005). However, biological soil crusts are very sensitive to disturbances, especially in soils with low aggregate stability such as sandy soils (Belnap & Gillette, 1997).

It is highly possible to connect the factors affecting the wind erosion directly or indirectly to each other as it was mentioned above. Most of the field studies evaluated the effects of these factors individually, or a combination of these factors on wind erosion as more data collection requires more labor, funding, and time. Environmental data and soil characteristics may change tremendously from one ecosystem to another ecosystem over time and space, and these factors and their interactions with each other will determine the intensity of wind erosion(Shao, 2008). Therefore, evaluating these factors on wind erosion as a whole provides useful information for future modeling and modeling errors.

To elucidate the interactions between wind erosion and site factors, some statistical approaches were used in the past, for instance, a large-scale study was conducted to assess the spatial distribution and temporal patterns of dust emission using a regression tree (Flagg et al., 2013). Random forest, a machine learning model, started gaining popularity in ecological studies (Cutler et al., 2007; Prasad et.,2006; Zanella et al., 2017) since it can handle complicated and non-linear ecological datasets (Cutler et al.,2007; Zanella et al.,2017). Moreover, the random forest is more suitable for these studies because a regression overfits as the data gets large (Fox et al.,2017). Unlike the random forest model, a decision tree can also fit exactly but fails to generalize on new samples (Faraway, 2005).

The overarching objective of this study was to describe ground-level sediment flux in southeastern Utah. To accomplish this aim and answer the study questions, a machine learning model (*i.e*., random forest) was used to assess the interactions between horizontal sediment flux and other factors (soil moisture, soil texture, precipitation, temperature, soil roughness, vegetation, grazing rates, canopy gap, and wind speed). More specifically, we 1) test the ability of a new machine-learning approach to describe the complex interactions that determine sediment flux in the sampling network, 2) test the importance of soil moisture by integrating soil moisture data into our new model of sediment flux, and 3) test model improvements achieved by extending sediment flux sampling in the network for an additional four years.

MATERIALS AND METHODS

To test the ability of a random forest model to describe variation in the sediment flux dataset, we re-analyzed sediment flux data (2007 to 2012) reported by Flagg et al. (2013). To test the ability of soil moisture data to improve estimates of variation in sediment flux, we simulated soil moisture from climate and soil texture data using the Hydrus 1D soil water movement model, then re-analyzed sediment flux data reported by Flagg et al. (2013) using both the random forest model and soil moisture data. Finally, we collected an additional four years of data (2015 - 2018) and constructed a new model of sediment flux using a random forest model, simulated soil moisture data and four years of additional data. Further, additional data on soil roughness (chain method (Saleh, 1993)) was added to the dataset. Additional single-parameter effects on sediment flux are also provided (e.g., vegetation type, season, grazing condition) since Flagg et al. (2013) reported them as important variables on sediment flux and soil roughness is also an important variable in the bare grounds between canopies (Okin et al., 2009; Shao, 2008). All variables, including climate and site characteristics, were divided into seasons based on the sediment mass collection date.

Study Area Description

The study area covers a roughly 6270 km^2 area of southeastern Utah, and extreme western Colorado in the Colorado Plateau (Fig. 4). Big spring number eight (BSNE; cite) collectors (52) were located between 1,000 and 2,200 m elevation (Flagg et al. 2013). The area has a dry climate characterized by hot summers and cold winters. Annual precipitation varies widely among sites (150 mm to 400 mm). Mean annual temperatures range from 9°C to 15 °C (Figs. 7 & 8). Dominant plant types (>25% total cover at times of field survey) in the locations of dust samplers (Fig. 4) are Pinyon-Juniper woodlands (*Pinus edulis* and *Juniperus osteosperma*), sagebrush shrublands (*Artemisia tridentata*), blackbrush and ephedra shrublands (*Coleogyne ramosissima* and *Ephedra virilis*), and perennial grasslands (*Achnatherum hymenoides, Hesperostipa comate, Bouteloua gracilis and Hilaria jamesii).* Also, some sites are dominated by various saltbrush species (*Atriplex confertifolia*, *A. corrugata*, and *A. gardneri*) and exotic annual plants including the annual grass cheatgrass (*Bromus tectorum*), and exotic annual forbs halogeton (*Halogeton glomeratus*) and Russian Thistle (*Salsola tragus*) (Duniway et al., 2016; Flagg et al., 2013). Mancos sites (<20%) were characterized by their lack of perennial vegetation (Laronne and Shen, 1982; Flag et al., 2013) and defined by Mancos Shale parent material (Duniway et al., 2018). Dominant plant types were grouped into grassland, blackbrush, sagebrush, saltbrush, and pinyon-juniper woodlands based on the lateral cover and vertical dimension of plants since these criteria were recommended to monitor wind erosion in vegetated desert ecosystems (Li et al., 2007). Sites with soil derived from Mancos Shales, which generally have a 0.8-2.3 cm thick physical crust formed by cementation of soluble salts and clays (Godfrey et al., 2008) were put in a separate group. Mancos sites have sparse vegetation that is sensitive to grazing disturbance, though can have high biological soil crust cover when protected (Duniway et al. 2018). Biological soil crusts are also common in undisturbed (e.g., grazed or traveled by humans) soils and known to be important for preventing wind erosion (Belnap & Gillette, 1997). Sand-sized particles dominated surface soil texture across study sites with a high variation ranging from 11.7% to 95.9% (0-10cm depth).

BSNE Moab Network Overview

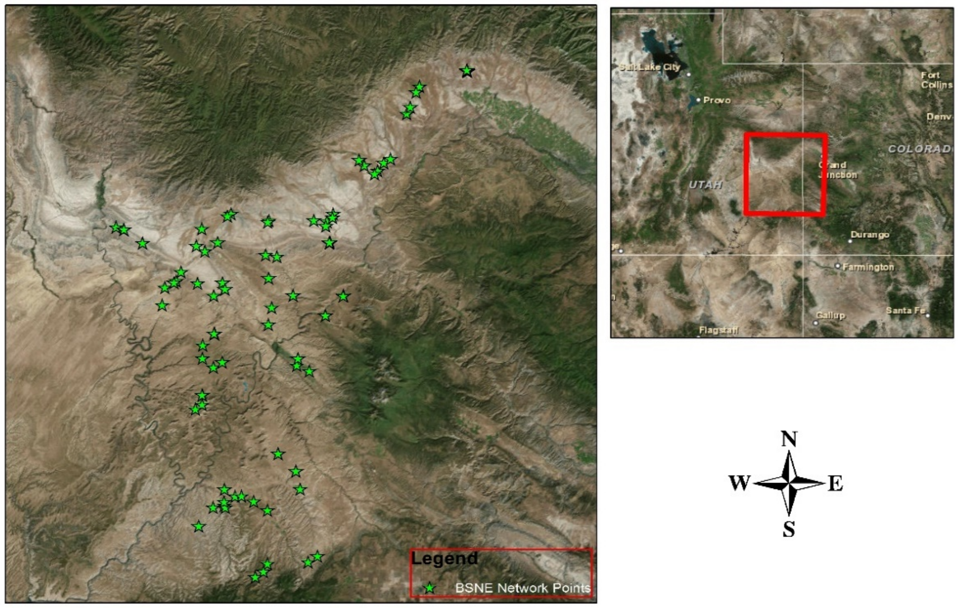

Figure 4 Location map of the study area, which includes the location of BSNE dust traps.

Meteorological Data

Before 2015, hourly wind speed from two stations ("Dugout Ranch") operated by USGS and Canyonlands Field Airport, and precipitation was obtained from six stations including 4 stations of National Oceanic and Atmospheric Administration (NOAA) (Flagg et al., 2013). After 2015, 15 anemometers to measure hourly wind speed at 3-meter heights were installed in 15 locations. Daily precipitation and temperature data were acquired from 24 different stations of USGS, NOAA and Canyonlands Research Center, Moab, UT Climate variables were averaged over sampling periods of sediment-flux (collection dates in March, July, October). Wind data was calculated as total hours of the wind exceeding 8 and 12 m s^{-1} as well as mean wind speed and mean peak speed (i.e., the maximum measured speed) during a sampling period. The sums and means of precipitation and temperature during a sampling period were also calculated.

Sediment Flux Monitoring

The U.S. Geological Survey (USGS) started a landscape-scale study to monitor sediment horizontal mass flux (*q*) on the Colorado Plateau in 2004 by installing 85 BSNEs (Big Spring Eight) (Flagg et al., 2013). Fifty-two of these samplers remain intact. BSNEs are commonly-used passive horizontal sediment flux collection devices (Fryrear, 1986; Ikazaki et al., 2009). BSNEs were used to collect dust mass at 15, 50, and 100 cm above the soil surface (Fig. 5). Each BSNE site was installed 50 m from unpaved roads and at least 1 m away from perennial vegetative obstructions (Flagg et al., 2013). Sample collections were performed three times a year on Spring (March), Summer (July), and Fall (October) before the samplers were filled to capacity. Dust collected in the boxes of the BSNEs was washed using deionized or purified water into plastic bags and dried in an oven at 60 ° C to constant mass (g) to the nearest ten-thousandth of a gram. Organic litter >1 mm in diameter or/and longer than 1 cm in length and dead insects (bees, flies, etc.) were weighed separately. Sediment-flux was calculated by dividing the recorded sample mass by the area of the BSNE opening (10 cm^2) and the sampling period duration at each collection height. Sediment flux is thus reported as grams' $meter^{-2}$ day^{-1}.

Figure 5 Photograph of one of the 52 dust collection sites used in this research, Moab, UT, USA. The ‘big spring number eight’ (BSNE) dust collectors have a wind vein to orient an opening into the wind at 15, 50, and 100 cm heights. BSNEs were fenced to exclude cattle. All collectors were located at least 50 m from a road.

Assessment of Physical Site Characteristics

Soil cover, including litter, rocks, vegetation, and biotic crusts was measured as in Flagg et al. (2013) using the line-point intercept method (Herrick et al., 2005). More specifically, 50 m long transects in the directions of 110, 220, and 330 azimuths from true north were located around BSNE samplers, April 2017. Vertical point hits in every 25 cm to the ground from a standard height next to the tapes were recorded as soil crusts, rock fragments, woody debris, plant litter, bare ground and plant species along each transaction. Canopy and basal gaps were also measured and classified into four groups as 25–50 cm, 50–100 cm, 100–200 cm, and larger than 200 cm (Herrick et al., 2005). Also, the mean values of both canopy and basal gaps were calculated (see Fig. 6).

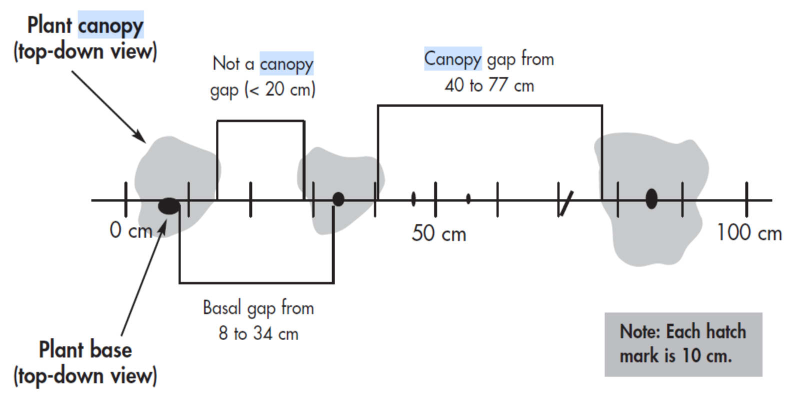

Figure 6 Demonstration of canopy gap and basal gap. If the plant-interspace is less than 20 cm, then it is not described as a canopy gap (Herrick et al., 2005).

Soil surface roughness (mm) was calculated with the chain method (Saleh, 1993). A 40-mm chain was placed on the soil surface at 9 points of every transect (in every 5 meters), and the measurement was repeated three times (in the angle of 110^0 ,220^0 ,330^0) to provide repetitions. After replacing the chain on the soil surface, the length of the chain was measured and recorded.

Soil Moisture Prediction

The soil water movement model, Hydrus 1D, was used to simulate continuous soil water content at 5, 15 and 30 cm depths in 10 of our collection sites (Simunek et al., 2008; Gupta et al., 2014). Hydrus simulates water and energy fluxes as a function of soil texture and meteorological data, including precipitation, temperature, radiation, wind speed, and relative humidity. Hydrus 1D model simulations were calibrated using observed soil moisture data (Simunek et al., 2012). Soil moisture was measured at 5 cm depths in 10 sites using capacitance reflectometry sensors (EC-5, Decagon Devices, WA, USA), though six of ten sensors were damaged by animals or people. Additional soil moisture data from 2004 to 2009 at 5 cm were provided from two stations operated by the U.S. Geological Survey (USGS). The data acquired from the stations were used to compare model predictions to the observed values using a regression model.

Data Analysis

a. **Variations in Sediment Flux**

Sediment fluxes under various soil covers and different parameters were evaluated in the previous study (Flagg et al., 2013), but with the extended and improved dataset, the variations in the sediment fluxes were re-observed and re-analyzed under different vegetation types and soil cover, land use, and seasons. For this purpose, some of the parameters in the dataset were categorized to observe how mean sediment flux changes under these circumstances. The year is divided into spring (March-July), summer(July-October), and winter (October-March) based on the collection date of sediment flux. The grazing condition of each site was evaluated as grazed, no graze, and some-graze. Dominant plant types were grouped into grassland, blackbrush, sagebrush, saltbrush, and pinyon-juniper woodlands, and mancos soil sites were also included to this group.

The distribution of sediment flux over soil surface covers (grassland, blackbrush, sagebrush, saltbush, mancos, and pinyon-juniper tree), conditions (grazed, some grazed and non-grazed), and seasons (spring, summer and winter) were investigated utilizing an analysis of variance (ANOVA) test (alpha=0.05) within groups. All sediment flux values were log-transformed to provide the assumptions of ANOVA (distribution and homogeneity). Although BSNEs were installed at 15 cm, 50 cm, and 100 cm, the analyses are conducted from the samples at 50 and 100 cm heights at all sites to avoid sample size limitations due to vegetation obstruction of BSNE rotation. Tukey's Honestly Significant Difference (HSD) posthoc test (confidence level =95%) was applied if the differences in sediment fluxes between vegetation types, seasons, and grazing conditions are statically significant. Then, the mean sediment flux (sum of sediment at 50 and 100 cm, and back-transformed values) of all the sites were reported.

b. **Random Forest Model**

One of the biggest challenges in environmental studies is to deal with complex and non-linear datasets. Ecological data are non-linear and have complicated interactions among the variables with lots of missing values which can be handled by random forest (Brieuc et al., 2018; Cutler et al., 2007). Machine learning techniques such as Random Forest (RF) (Breiman, 2001) are widely used to handle complex variables and RF provides better results compared to most methods in common use (Brieuc et al., 2018; Cutler et al., 2007; Fox et al., 2017; Prasad et al., 2006; Zanella et al., 2017). Therefore, using RF can manifest better understanding of the interactions among the forces driving wind erosion and determining most effective factors, which will be helpful to choose the variables (soil moisture, soil texture, wind speed, etc.) to put into the further modelling of susceptible places to wind erosion and shed light on why wind erosion occurs. We used this machine learning model to describe the relationship between sediment flux and the factors affecting wind erosion. More specifically, a random forest modeling was used to 1-) compare the performance of the random forest model against a regression tree for the data used in the previous study, 2-) investigate the impact of soil moisture on wind erosion with the same dataset, 3-) observe the improvements of the model by extending dataset, 4-) to determine the most effective factors on wind erosion in the study area.

A dataset was prepared to run a random forest model in the R environment using a randomForestSRC package (Ehrlinger, 2014). Plant community, season, peak wind speed, total hours of wind >8 ms^{-1}, total hours of wind >12 ms^{-1}, seasonal precipitation, antecedent precipitation, soil texture, soil stability, BSC cover, annual plant cover, percent perennial plant cover, and plant gap means were used as predictor variables since they were used as predictors with 951 observations in the previous study. The proportion of variation of the response variable explained by the tree (variation explained) determines the strength of a regression tree or a random forest regression tree (Brieuc et al., 2018). Therefore, model results were compared to evaluate the power of a random forest model based on variance explained.

Predictions of soil moisture at three different depths (5,15 and 30 cm) over the study area were added to the dataset to investigate the impacts of soil moisture on wind erosion, and then the random forest model was re-run. In contrast to traditional methods, the random forest model has a unique variable selection method (Cutler et al., 2007; Zanella et al., 2017). Briefly, variable importance (VIMP) is determined by a prediction error approach (Ehrlinger, 2014; Hastie et al., 2009), the difference between the error rates of modified and original data, divided by the standard error, is a measure of the importance of the variable (Cutler et al., 2007; Ehrlinger, 2014). Therefore, variables with large VIMP values are more important (Ehrlinger, 2014). Based on VIMP criteria, the significance of soil moisture compared to the other parameters was revealed. Moreover, partial dependence plots (Hastie & Tibshirani, 2000) can be utilized to illustrate the association between the individual variable and response variable (Cutler et al., 2007). After extending the dataset with new collections of sediment flux and soil moisture, the improvements in the random forest model was examined to determine if further data collections were necessary or not.

Unlike other methods, the random forest does not require N-fold cross-validation since an out-of-bag (obb) is almost identical to that obtained by N-fold cross-validation and is used to get estimates of variable importance (Hastie et al., 2009). The optimization of random forest can be conducted by adjusting two parameters: the number of trees grown (ntree) per forest and the number of predictors to randomly sample at each node (mtry) (Goldstein et al. 2010). Increasing the values of ntree and mtry will generally develop the accuracy of the random forest until the OOB, or PVE (proportional variance explained) catches a plateau (Brieuc et al., 2018; Goldstein et al., 2010). After acquiring a stable value of OBB, increasing the values of ntree and mtry do not develop predictive power (Brieuc et al., 2018).

RESULTS

Climate Data Analysis

Climate data varied widely across study years, providing inference to a wide range of climate conditions (Figs. 7-9).

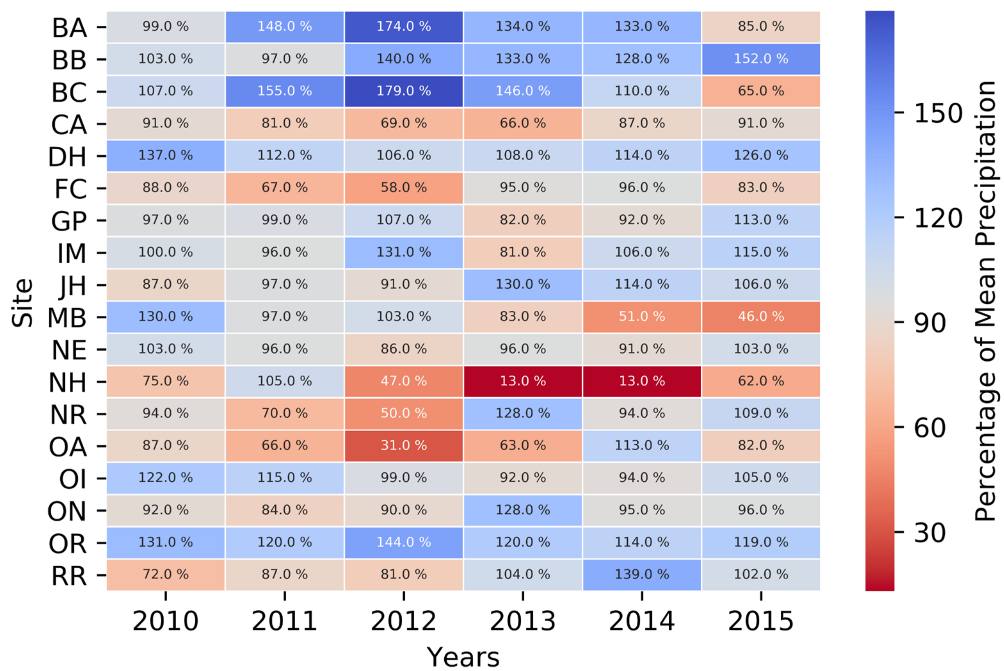

Figure 7 The percentage of mean precipitation for each site to the annual mean precipitation is shown. For 2012, BA and BC sites had the most precipitation (174% and 179%, respectively), these sites had 74% and 79% more precipitation than average precipitation for the year. For 2013 and 2014, NH site had the lowest precipitation percentage (87% less precipitation than the average).

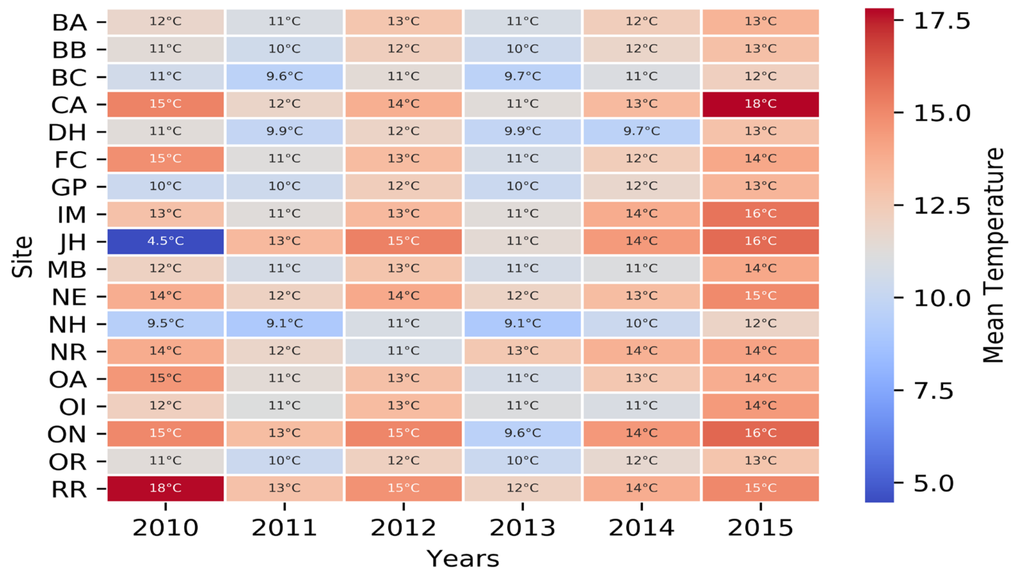

Figure 8 The distribution of annual mean temperature (^{0}C) based on sites and years. Mean temperature ranges from 4.5 to 18 ^{0}C over the sites and years.

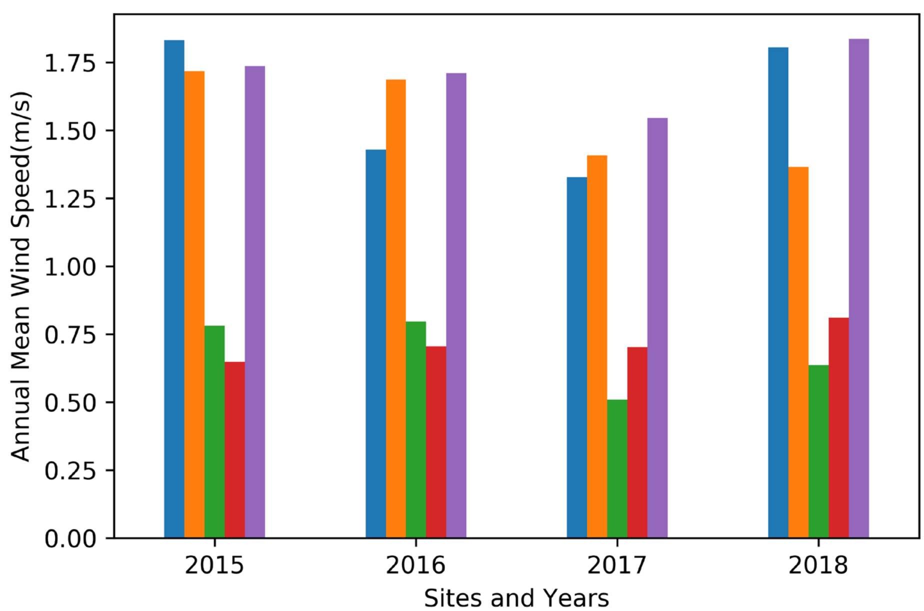

Figure 9 Annual mean wind speed distribution in five study areas over the years (from 2015 to 2018 for new collections). Each bar shows the mean value of wind speed for a different site. Wind speed changes from 0.51 m second^{-1} to 1.84 m second^{-1} for B16 (blue), B8 (orange), Hart2 (green), Hatch1 (red), and RO-FC (purple).

Simulated estimates of soil moisture at 5 cm were correlated with observed soil moisture at 5 cm ($F_{1,3813}$ =3382, $p < 0.05$, $R^2 = 0.47$).

Sediment Flux Variations

Sediment flux variation was evaluated under vegetation types and soil cover, grazing conditions, and seasons using the whole dataset from 2004 to 2018, with a data gap from 2013 to 2015. The mean sediment flux (sum of sediment at 50 and 100 cm, and back-transformed values) of all the sites under different vegetation covers range from 6.95 ± 5.91 g m^{-2} day^{-1} to 18.76 ± 18.76 g m^{-2} day^{-1}. Sediment flux differed among vegetation cover and soil type ($F_{5,\ 1460} = 5.705$, $p < 0.001$). Tukey's Honestly Significant Difference (HSD) post-hoc test (confidence level = 95%) revealed differences among vegetation types (Fig. 10). Mean sediment flux was the lowest under pinyon-juniper sites (6.95 ± 5.91 g m^{-2} day^{-1}) and the highest in the blackbrush (18.76 ± 18.76 g m^{-2} day^{-1}).

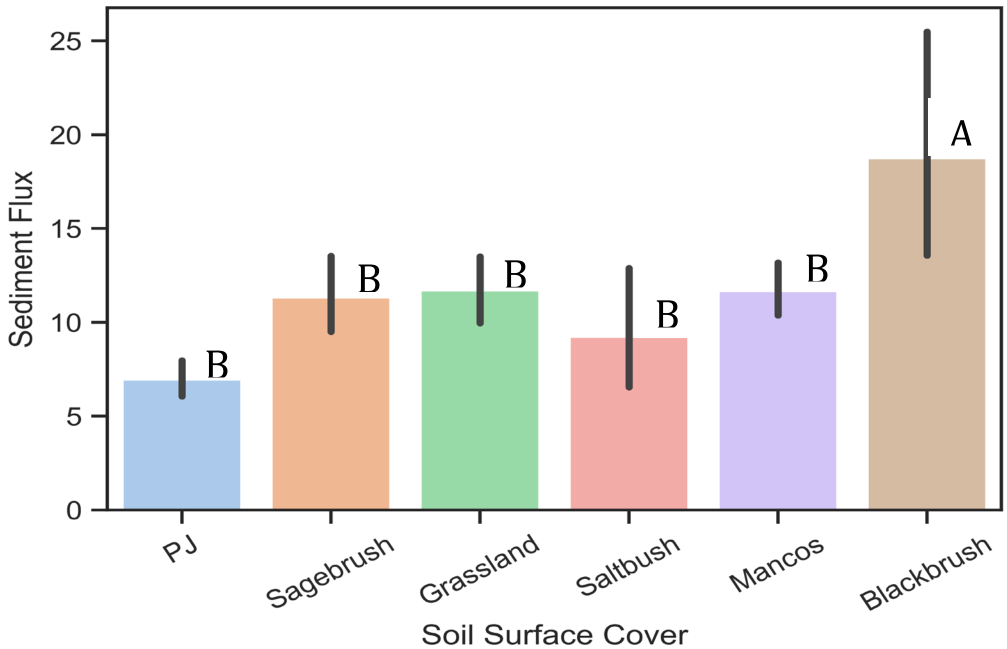

Figure 10 The distribution of mean sediment flux (g m^{-2} day^{-1}) under different vegetation types and soil cover. Sediment flux (g m^{-2} day^{-1}) is the highest in Blackbrush while it is the lowest in Pinyon-Juniper (PJ). According to Tukey's HSD post-hoc test (A-B), there was a significant difference in the mean values of sediment fluxes between Blackbrush and other vegetation types.

Mean seasonal sediment flux ranged from 9.66 ± 15.25 g m^{-2} day^{-1} to 13.78 ± 20.66 g m^{-2} day^{-1} among the grazing conditions and from 4.09 ± 5.92 g m^{-2} day^{-1} to 17.29 ± 19.66 g m^{-2} day^{-1} among seasons over the sites. Sediment flux also differed among seasons ($F_{2,1463} = 405.8$, $p < 0.001$) and grazing conditions ($F_{2,1453} = 8.255$, $p < 0.001$) (Fig. 11). Sediment flux was greatest during the spring (17.29 ± 19.66 g m^{-2} day^{-1}) and summer (12.45 ± 17.48 g m^{-2} day^{-1}) while it was the lowest in the winter season (4.09 ± 5.92 g m^{-2} day^{-1}). Sediment flux was greater under the grazed conditions 22.20 ± 22.72 g m^{-2} day^{-1} in spring and 15.94 ± 24.10 g m^{-2} day^{-1} in summer while no-graze has highest sediment flux (4.88 ± 5.50 g m^{-2} day^{-1}) in the winter (Fig. 11).

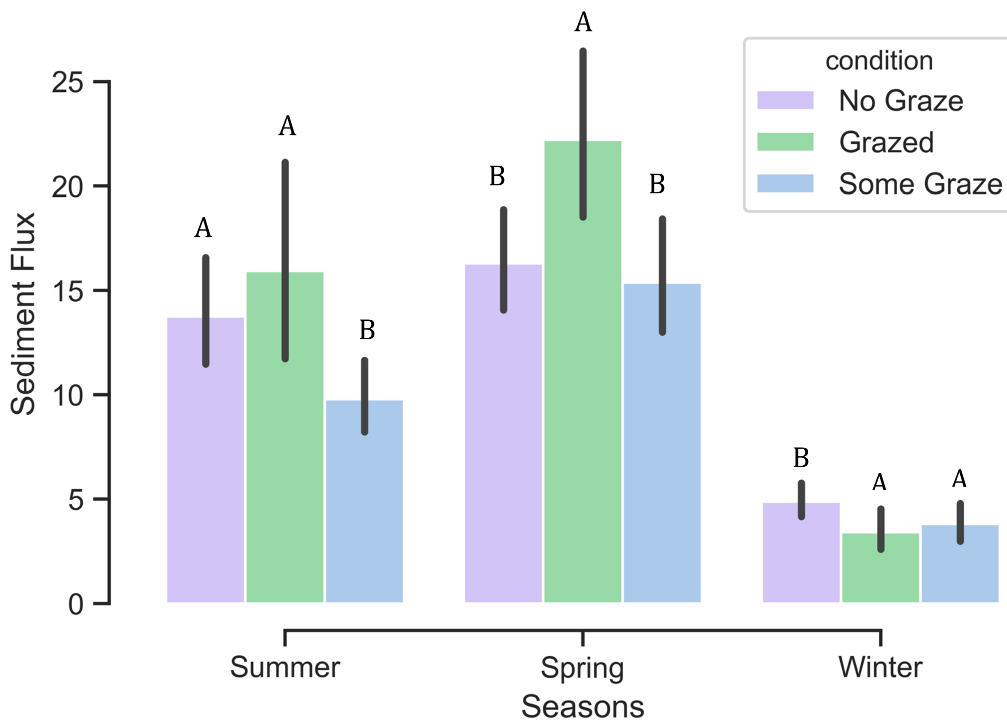

Figure 11 The distribution of mean sediment flux (g m^{-2} day^{-1}) by seasons (Winter, Summer, and Spring) and conditions (Grazed, Some Graze, and No Graze). Sediment flux (g m^{-2} day^{-1}) was the highest in the spring season and grazed condition. According to Tukey's HSD post-hoc test (A-B), there were significant differences within seasons and grazing conditions.

Random Forest Outputs

The random forest model was performed with 951 observations for sediment flux (the dataset of the previous study), the best model for this dataset explained 60.56% of the variance (MSE=0.08). Variable importance decreased as follows: wind speed (m $second^{-1}$), precipitation (mm), soil texture (%), and bare ground percentage as primary drivers of sediment flux over the drylands of southern Utah from 2007 to 2012 (Fig.13).

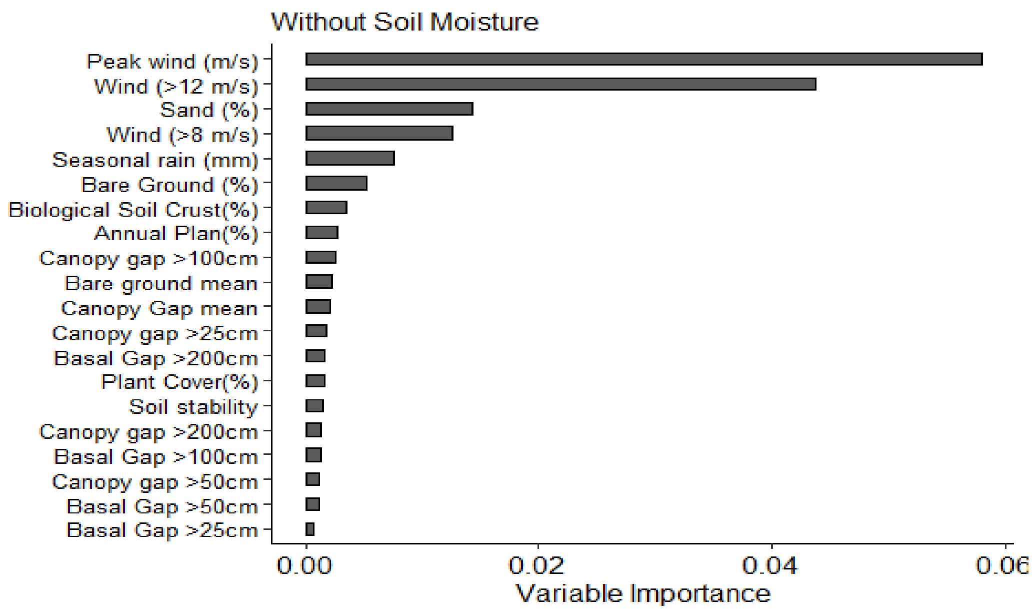

Figure 12 Variable importance in random forest model of seasonal sediment flux with 951 observations. Wind speed, sand, seasonal rain, bare ground, and biological soil crust were the top five most important factors while canopy gap and basal gap were the least important variables describing sediment flux.

In the random forest model, mean square error (MSE =0.06) and variance explained were calculated using Out of Bag Errors for the second model to evaluate the effects of soil moisture on sediment flux. Soil moisture data improved model performance. The variance explained for the best random forest model was 64.47%, with an increase of 3.91% compared to the previous model performance. The ranks of wind (>8), wind (>12 m second^{-1}), peak wind (m second^{-1}), and sand (%) did not change in the variable importance table (Fig.14). However, the contribution of seasonal rain (mm) decreased with added soil moisture predictions at 5, 15, and 30 cm depths.

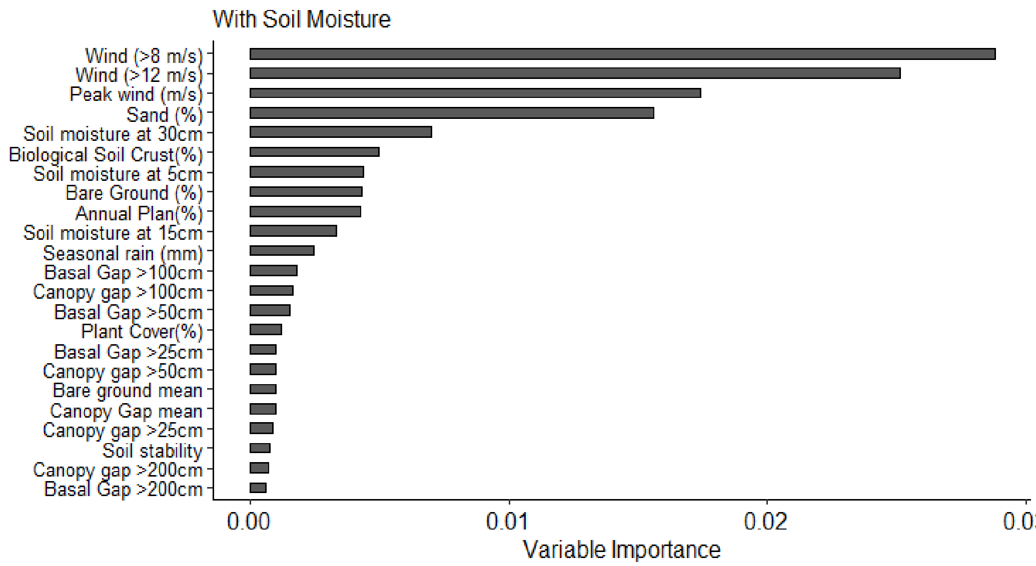

Figure 13 Variable importance in random forest model of seasonal sediment flux with 951 observations and the impact of soil moisture on sediment flux. Wind speed, sand content, soil moisture, biological soil crust, and bare ground were the top five most important factors while canopy gap and basal gap were the least important variables describing sediment flux.

Finally, we tested the random forest with the full dataset from 2006 to 2018. The variance explained by the model was 80.6% with 1468 observations (MSE=0.06). We took out wind speed (>8 and >12 m/s) since there were missing values in the wind gust and it cropped the numbers of observations used by the model. However, we added soil roughness measurements. Wind speed (m/s), seasonal precipitation (mm), soil moisture (%) (at all levels), sand content (%), and biological soil crust were most important factors (Fig. 15).

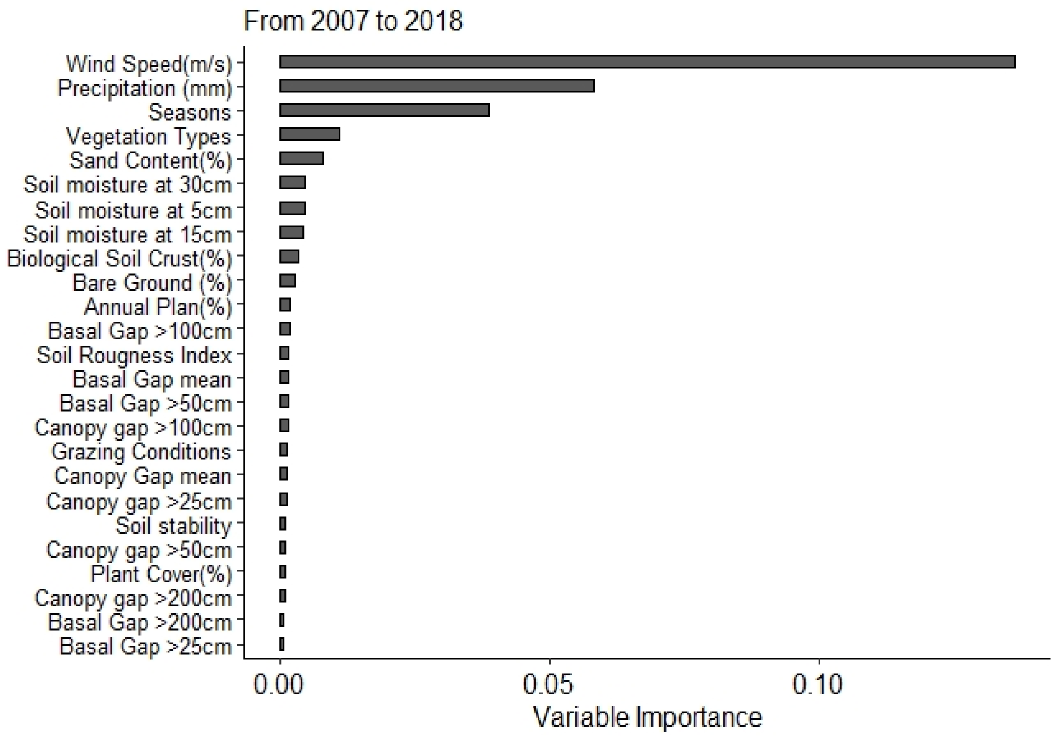

Figure 14 Variable importance in random forest model of seasonal sediment flux with 1468 observations from 2006 to 2018. Wind speed, seasonal precipitation, seasons, vegetation types, sand, soil moisture, biological soil crust, and bare ground were top ten most important factors while canopy gap and soil stability were the least important variables describing sediment flux.

DISCUSSION

Here we used a spatially and temporally extensive dataset to model sediment flux in the Colorado Plateau. By using a machine learning model, simulating soil moisture with a soil water movement model and increasing sample size (54% more data from a new four-year sampling period), this research improved the explanation of variance in sediment flux from 56% to 81%. Increasing sample size allowed the greatest improvement sediment flux variance explained. This likely occurred because models of sediment flux must account for interactions among many correlated and simultaneously varying parameters such as wind speed, vegetation type, soil texture, and soil moisture and carry over the effects from year to year. While this dataset proved very effective at describing variation in sediment flux in the study region, this research highlighted the need for temporally and spatially large datasets for understanding sediment flux. We also tested the ability of random forest analyses and soil moisture data to improve model estimates of sediment flux. Random forest analyses provided a moderate improvement (i.e., 56 to 64%) and are recommended for future research. Estimates of soil moisture provided surprisingly small improvements in model performance, likely because previously-used precipitation data were likely to be well correlated with our new soil moisture estimates.

Consistent with previous research, our model (Fig. 12) indicated that wind speed is primary determinant of sediment flux in the study area. In the contrast to the previous study at the study site, but consistent with studies in other systems, we found a strong relationship between sediment flux and precipitation (Bach et al., 1996; Urban et al., 2009). Also, our new analyses detected an important role of sand content, bare ground, and biological crust. Biological soil crust is a good protector for bare grounds, but sandy soils and bare grounds are more susceptible to wind erosion. Low water-holding capacity, weak aggregate stability, and insufficient organic matter content of sandy soils make them more vulnerable to wind erosion. So, bare soil surfaces with high sand content and low soil moisture are exposed to high wind speed, thus resulting in high sediment fluxes.

Adding soil moisture data for 5, 15, and 30 cm depths (Fig. 13), increased the variance in sediment transport explained from 61% to 64%, presumably because soil moisture is important for controlling entrainment and transport of sediment through adhesion (Lancaster & Nickling, 1994; Nickling & Neuman, 2009). Typically, in wind erosion studies, only soil moisture in the top few cm are considered (Selah and Fryrear,1995; Chen et al., 1996; Bergametti et al., 2016), but here we tested for the effects of soil moisture at 5, 15 and 30 cm. Interestingly, we found that simulated soil moisture at 30 cm was more important than soil moisture at 5 or 15 cm. It is not clear why this occurred, though it is possible that deeper soil moisture was associated with greater plant growth, root exudation, and other factors that affect sediment flux. Furthermore, the contribution of seasonal rain to the model performance decreased after adding the soil moisture predictions suggesting that these variables explain similar patterns of variation in the dataset. This shows that soil moisture predictions (4.83 %) explained more variance than seasonal rain (2.93%) did.

After adding new four years of data from 2015 to 2018, the contribution of precipitation to the model increased and explained more variance than soil moisture predictions (Fig. 14). Therefore, precipitation can be an alternative to limit wind erosion if soil moisture data is not available since it directly affects soil moisture (Bergametti et al., 2016).

Unfortunately, most of the factors affecting wind erosion in this model except for vegetation types, biological soil crust, and site conditions cannot be controlled; it is likely to increase over time with climate change. The effects of vegetation types on sediment flux were consistent with the results from previous studies (Belnap et al., 2009; Floyd & Gill, 2011; Flagg et al., 2013). The vegetation types played an important role as the aerodynamic roughness in our model because they are a representation of the capacity of the surface for absorbing momentum and is important quantity in wind erosion studies (Crawley et al., 2003; Marshall, 1971; Wolfe et al., 1993). Different vegetation types have different bare grounds between canopies. Size, shape, and spatial distribution of bare grounds between canopies in arid and semi-arid regions determine the susceptibility level to wind erosion (Aguiar & Sala, 1999; Okin et al., 2009) and increase sediment flux (Li et al., 2007; Tchakerian, 2014). Sediment flux was highest under blackbrush-dominated sites (18.76 ± 18.76 g m-2 day-1) while it was the lowest in pinyon-juniper woodland (6.95 ± 5.91 g m^{-2} day^{-1}). The differences of sediment flux between vegetation types and mancos sites can result from the bare grounds, the amount of precipitation in these grounds, the size and structure of vegetation, disturbance of soil surface by animals and people, and wind speed exposed. Munson et al. (2011) reported decreases in vegetation covers (blackbrsuh, sagebrush, saltbrush, and grasslands) of the Colorado Plateau with global warming. This may cause increases in sediment transportation in the future because the bare ground will increase as the vegetation cover decreases. It is also because horizontal sediment flux is correlated with climate parameters as it is reported in the previous studies (Nauman et al., 2018). For example, higher temperature and low precipitation give rise to increases in horizontal sediment flux in this area (Munson et al., 2011), and our model also showed similar results. Sediment flux is mostly a function of climate variables such as wind speed and precipitation.

Nauman et al. (2018) in this area reported that aeolian sediment transport increases as a result of surface disturbances owing to grazing and off-road vehicle use on sensitive soils and landscape settings, with climate change. Our findings also illustrate that biological soil crust, vegetation types, and grazing conditions are the factors that we can manage. Biological soil crust can increase the infiltration rate and soil moisture content (Bowker et al., 2006), which can support vegetation communities and increase the resistance to wind erosion in bare grounds. Biological soil crusts were very sensitive to disturbances due to grazing and off-road vehicles, so high biological crusts were mostly observed in the undisturbed areas such as National Parks. The grazing conditions didn’t provide a big contribution to our random forest model (Fig. 14), but sediment transportation was also higher under the grazed conditions (10.665 ± 16.52 g m^{-2} day^{-1}) in summer and spring (Fig. 11) likely because the animals and human-induced causes disturbed the soil surface, thus reduced the resistance to the wind power (Belnap et al., 2001; Lemos & Lutz, 2010). The result demonstrates that more detailed researches are needed to evaluate livestock management approaches since it has a big effect on soil surfaces, especially on soil crusts. For instance, Moncos Shale has sparse vegetation that is sensitive to grazing disturbance, but can have high biological soil crust cover when protected (Duniway et al. 2018). Contribution of biological crust to the model was high, but the amount of biological crust over the study area except for National Parks was low because of the disturbances. Also, the ground cover in these systems can intensify and persevere during drought when livestock is excluded (Duniway et al., 2018). Therefore, future research on and management of biological soil crust, vegetation types, and grazing conditions are essential to wind erosion modeling since they are the important variables that we can manage to amend the bare grounds of the drylands.

Results inform our current understanding of wind erosion processes in drylands by evaluating the interactions between the factors and wind erosion at a landscape scale. Random forest model improved the variance in sediment transport explained relative to regression tree analysis. Soil moisture predictions provided a better understanding of wind erosion by improving model predictions, but seasonal rain can be an alternative if soil moisture is not available. However, increasing sample size from roughly 1,000 to 1,500 sediment flux collections allowed the largest improvement in variance in sediment flux explained. Results are expected to be helpful to managers for recovery works, scientists to choose variables for further modeling or local people to increase the awareness of wind erosion impacts on nature. For example;

- Long term and large-scale coordinated monitoring and data collections allow scientists to better deduce the impacts of land management policies and practices on wind erosion. This may even lead to interdisciplinary efforts which will be necessary for a better understanding on how to best model the processes of wind erosion.

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