SPATIAL AND TEMPORAL PATTERNS OF DUST EMISSIONS IN SEMI-ARID LANDSCAPES, SOUTHEASTERN UTAH, USA: 2008-2011

by

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This thesis entitled: Spatial and Temporal Patterns of Dust Emissions in Semi-Arid Landscapes, Southeastern Utah, USA, was written by Cody Benjamin Flagg and has been approved for the Department of Geological Sciences.

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Date__________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Abstract

Cody B. Flagg (M.S., Geological Sciences)

Spatial and temporal patterns of dust emissions in semi-arid landscapes, southeastern Utah, USA: 2008-2011.

Thesis directed by Associate Professor Jason C. Neff

Aeolian dust can influence nutrient availability, soil fertility, plant interactions, and water-holding capacity in both source and downwind environments. Measuring dust emission and deposition can reveal spatial and temporal patterns of dust flux, informing various ecological and atmospheric models, as well as advancing understanding of aeolian dust processes. Quantifying controls, flux rates, and locating sources of dust is particularly important to regional-scale environmental dynamics, as dust from the Colorado Plateau has recently been linked to changes in the hydrology and nutrient cycling of the San Juan Mountains. Vegetation, ground cover, land-use, and climate patterns affect dust generation in different ways. Previous studies have documented the effects of these variables on dust flux in dryland settings of the western United States, but very few have identified sources, flux rates, and controls on the Colorado Plateau. This study integrates dust emission, ecological, and climate data collected over three years to elucidate spatial and temporal patterns of dust flux from the eastern Colorado Plateau in southeastern Utah.

A network of 108 passive sediment collectors spanning numerous types of ecosystems, soil types, land-use histories, and geologic settings covering approximately 4000 square kilometers across southeastern Utah was used to sample horizontal sediment emissions. The sample archive dates to early 2008 and is currently the largest known record of field-scale dust emissions for the southwestern United States. Samples were collected every four months from the sediment collectors at heights of 15 cm up to one meter. Line transects were established at each collection site to measure vegetation cover, collect soil samples, and estimate surface-soil stability.

Dust flux peaked during the spring months in all plant-community types, related to higher, sustained surface wind speeds that begin in the early spring. Dust flux was lowest during the winter period when surface wind speeds are typically low. Contrary to other studies on dust emissions, antecedent precipitation one, two, and three seasons prior to sample collection did not significantly influence emission rates. Flux rates also did not vary significantly among soil types. Sites dominated by shrubs and/or non-native plants had higher flux rates compared to grasslands, woodlands, and sites with high biological soil-crust cover. Physical factors controlling dust emissions were complex and varied from one vegetation type to another. Vegetation type, seasonal wind patterns, and certain physical site characteristics are important factors in controlling dust emission rates in southeastern Utah.

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Chapter 1

1. Introduction

Dryland regions, arid and semiarid, cover approximately 41% of the earth's surface (MEA, 2005). These regions are sensitive to alterations in climate and land-use patterns (Mahowald et al., 2006), particularly because these types of changes cause large, rapid, and irreversible transitions from stable to highly degraded ecosystems (Bestelmeyer, 2006; Bestelmeyer et al., 2011; Webb and Strong, 2011). Wind erosion drives dryland transitions by removing key nutrients and reducing the water-holding capacity of soils (Li et al., 2007; Neff et al., 2005), potentially reducing ecosystem productivity. Changes in soil properties and vegetation cover can directly affect wind erosion processes as they exert a strong influence on the type and amount of aeolian sediment produced from an area (Okin et al. 2006). Aeolian transport and deposition can affect downwind systems at landscape, regional, and global scales (Webb and Strong, 2011). Sediment transported from drylands reduces visibility in protected National Parks and wilderness airsheds (Kavouras et al., 2007), alters snow chemistry (Rhoades et al., 2010), accelerates the rate of snowmelt (Painter et al., 2007), and fertilizes ecosystems with nutrients (Chadwick et al. 1999; Reynolds et al. 2001; Lawrence et al. 2010). Whereas a large amount of research has been carried out on wind erosion in deserts, the sources, drivers, and controls of wind erosion are still relatively unknown for partly vegetated regions throughout the world (Okin et al. 2011).

Vegetation is the single most important factor in protecting soil surfaces, as bare soil alone offers very little protection from wind erosion (Belnap & Gillette 1998; Okin

2008). Vegetation also influences patterns of wind erosion at multiple scales, from the individual plant up to the large-scale spatial distribution of various plant communities (Okin et al. 2006). Plants diminish the shear stress of wind on the surface by reducing wind momentum, and also trapping particles in their entrainment area (Okin et al. 2006; Floyd & Gill 2011). The type and amount of plant cover can affect the severity of wind erosion: high perennial grass cover, higher woody plant cover, and higher average plant height all correspond to lower erosion rates in drylands (Breshears et al. 2009). Other studies indicate that shrubland communities dominated by different species exhibit highly variable erosion rates (Gillette 2004; Bergametti & Gillette 2010; Floyd & Gill 2011), suggesting that vegetation interacts with other factors to protect soils from wind erosion.

Certain characteristics of surfaces and soils variably affect the severity of wind erosion at the spatial scale of centimeters to meters. More heterogeneous or “rough” surfaces reduce potential erosion compared to flatter ones by extracting momentum from wind; woody debris, plant litter, gravel, and rocks all increase soil surface roughness (Herrick et al. 2005; Okin et al. 2006). Soil aggregation is also an important aspect of site erodibility, as particles that are physically bound together by plant roots, soil organic matter, and micro-organisms are more resistant to erosion (Tisdall 1996; Herrick et al. 2001; Roose & Barthe 2002). Biological soil crusts (BSC), a complex association of lichen, moss, and cyanobacteria, are particularly important to drylands as they bind soil particles together, increase soil fertility by fixing nitrogen, and can cover as much as 70% of the surface in certain areas (Belnap & Gillette 1997; Belnap 2003; Chaudhary et al. 2009). Soil stabilizing characteristics are particularly sensitive to human land-use activities however, and can take decades to recover from disturbance (Reynolds 2003; Neff et al. 2005; Belnap et al. 2007).

Short and long-term climate patterns can influence dryland erosion processes by interacting with and affecting vegetation and soil surfaces characteristics (Bach et al. 1996; Okin & Reheis 2002; Ravi & D'Odorico 2005; Urban et al. 2009). Dry winters in the Sonoran and Mojave deserts can inhibit subsequent plant growth, thus leading to more dust storms (MacKinnon et al. 1990; Bach & Brazel 1996; Urban et al. 2009). Alternatively, heavy precipitation in certain years causes increased dust emission from wet, saline playas (Reynolds et al. 2007) and alluvial flats (McTainsh et al., 1999). Soil moisture variability, related to precipitation patterns, can affect wind erosion potential as wetter soils tend to be more cohesive and thus have higher erosion thresholds (McTainsh et al., 1998; Ravi and D'Odorico, 2005). The link between aeolian sediment movement and high wind speeds has long been known (Bagnold, 1941), and subsequently studied in great detail (Shao, 2008). Peak wind speeds tend to occur more frequently during certain time periods (Goudie & Middleton 1992; Prospero 2002) and can interact with land-use related disturbances to produce large quantities of suspended sediments (van Donk et al. 2003; Belnap et al. 2009; Miller et al. 2012).

A significant portion of wind erosion research has focused on the physical processes and causes of wind erosion in sand dunes (Namikas, 2003), un-vegetated dry or ephemeral lakes "playas" (e.g. Gillette et al. 1997; Reheis 2006; Reynolds et al. 2007) or agricultural fields (Bielders et al., 1999). Only more recently have studies begun to quantify wind erosion on partially vegetated surfaces both disturbed (Belnap et al. 2007; Jayne Belnap et al. 2009; Marith C. Reheis & Urban 2011), and undisturbed

(Gillette & Pitchford 2004; Bergametti & Gillette 2010; Floyd & Gill 2011; Sweeney et al. 2011). There are relatively few data on the timing, background flux rates, and spatial variability of dust emission events from the Colorado Plateau as well as numerous other arid and semi-arid regions of the world. The main objective of this study was to measure sediment emission rates at the site-scale across various plant community and soil types across southeastern Utah, as well as to quantify various site- and landscape-scale controls on sediment-flux. I examine how sediment flux varies with season, soil type, elevation, and mostly undisturbed plant communities, and evaluate how certain physical site characteristics and weather patterns interact to influence the timing and strength of sediment emissions for samples collected from June 2008 to June 2011.

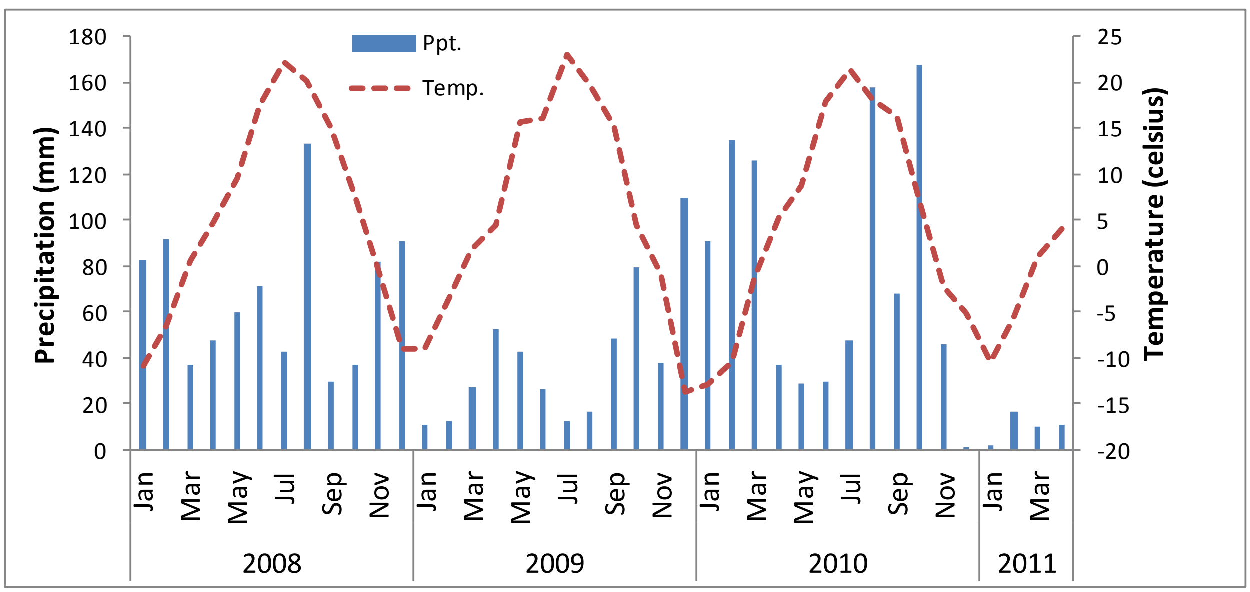


Figure 1. Mean precipitation and temperature data compiled from Moab, UT, CNP – “The Neck”, CNP - “Needles”, and ANP Western Regional Climate Center weather stations for the study period.

2. Materials and Methods

2.1 Description of Study Area and Design

Sediment flux measurements were conducted over a large area of southeastern Utah, near Moab, Utah, from June 2008 to December 2011. The eastern part of the Colorado Plateau is a semi-arid desert that receives less than 300mm of precipitation annually, with as much as 40% of the precipitation experienced as summer monsoons from July to August (Figure 1). The geology of this region is complex, ranging from Cretaceous and Jurassic aged shale to Quaternary aged sandstone.

Eighty-five individual sites were established in a variety of eco-sites, soil types, elevations, and levels of human disturbance (Figure 2A, Table 1). Each study site was outfitted with a “Big Springs Number Eight” (BSNE) sediment collector. The BSNE is a passive, horizontally oriented wind-aspirated sediment sampler installed onto a pole and attached to a wind vane that orients the collector into the wind (Fryrear & Saleh, 1993). Most study sites had three collectors mounted per pole at 15cm, 50cm, and 100cm from the soil surface, but 30 sites only had 50cm and 100cm collectors installed. The measurement sites include the common vegetation types found in the study area. These include Pinyon-Juniper woodlands (*Pinus edibulus* and *Juniperus osteosperma*), sagebrush and greasewood shrublands (*Artemisia tridentata* and *Sarcobatus vermiculatus*), blackbrush and ephedra shrublands (*Coleogyne ramosissima* and *Ephedra virilis*), saltbush shrublands (*Atriplex confertifolia*, *A. gardneri*, and *A. corrugata*), and perennial grasslands (*Bouteloua gracilis* and *Hilaria jamesii*).

Table 1. Description of the different types of sites in this study by dominant vegetation cover, plant functional class, surface soil component, and the number of BSNE samplers present for that particular site type.

Dominant Plant Species	Dominant Veg./Cover	Functional Class	Soil Component	# Sites	Notes
P. edibulus, J. osteopora	Pinyon-Juniper	Woodland	Rizno	8	
A. tridentata, A. filifolia	Sagebrush	Shrubland	Begay / Ignacio	18	
C. ramosissima	Blackbrush	Shrubland	Moenkopi	4	Low elev.
	Blackbrush	Shrubland	Begay	3	High elev.
None	Biological crust	Mancos	Toddler-Ravola	6	Only cyano. present, no lichen/moss
S. iberica, B. tectorum	Invasives	Mancos	Toddler-Ravola	14	
Atriplex spp.	Saltbush	Mancos	Hanksville / Begay	16	
S. vermiculatus	Greasewood	Mancos	Toddler-Ravola	3	
B. gracilae	Grass	Grassland	Begay	10	
H. jamesii	Grass	Grassland	Begay	3	

Site placement was focused on sampling locations distributed across the two most widespread general soil types derived from Mancos shale and Navajo and Kayenta sandstone formations (Figure 2B). Elevation among sites ranges from 1368m to 2231m above sea level. Most sites were located on Bureau of Land Management lands (BLM) as the BLM manages roughly 40% of the land within these counties, and these sites were considered to be representative of rangelands throughout the region. 90% of these sites were located within active grazing allotments, which can cover large, diverse swaths of land. Several sites were located within the boundaries of Canyonlands National Park (CNP) and Arches National Park (ANP), and have thus been excluded from grazing since the early 1970s (Belnap et al. 2009; Munson et al. 2011). Sites located outside of CNP and ANP were variably affected by grazing throughout the study period. In general, sites were established in places that did not appear to have any recent or severe disturbances. Animal-unit-month data, an estimation of the forage an animal consumes in a month, were not available for all sites; therefore, it was difficult to quantify impacts by cattle grazing. In any case, cattle were observed infrequently near study sites and appeared to be widely distributed across large areas. Direct soil surface disturbance due to cattle grazing was thus assumed to be low throughout the study period. The one exception are the sites on Mancos soils that were paired between sites recently disturbed by intense grazing in 2007 (labeled as “Mancos Blowout”, or “MB”), and nearby sites that were undisturbed at time of establishment (“Mancos Control”, or “MC”).

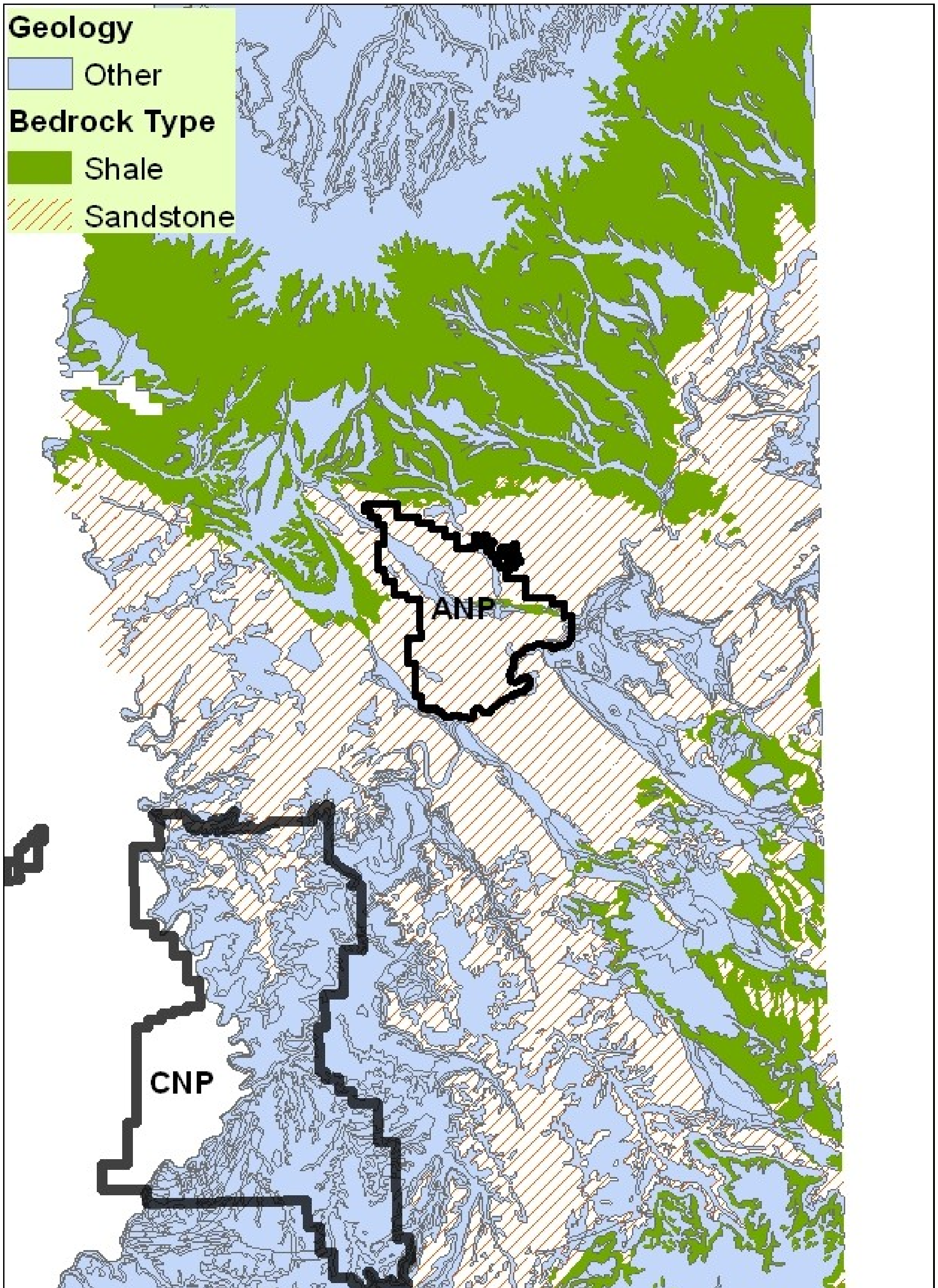


Figure 1B. Geologic map of study area denoting the two major bedrock types, shale and sandstone, studied here. Black outlines represent boundaries of Canyonlands National Park (CNP) and Arches National Park (ANP). Map is derived from data provided by the Utah Geological Survey (http://geology.utah.gov/maps/gis/index.htm).

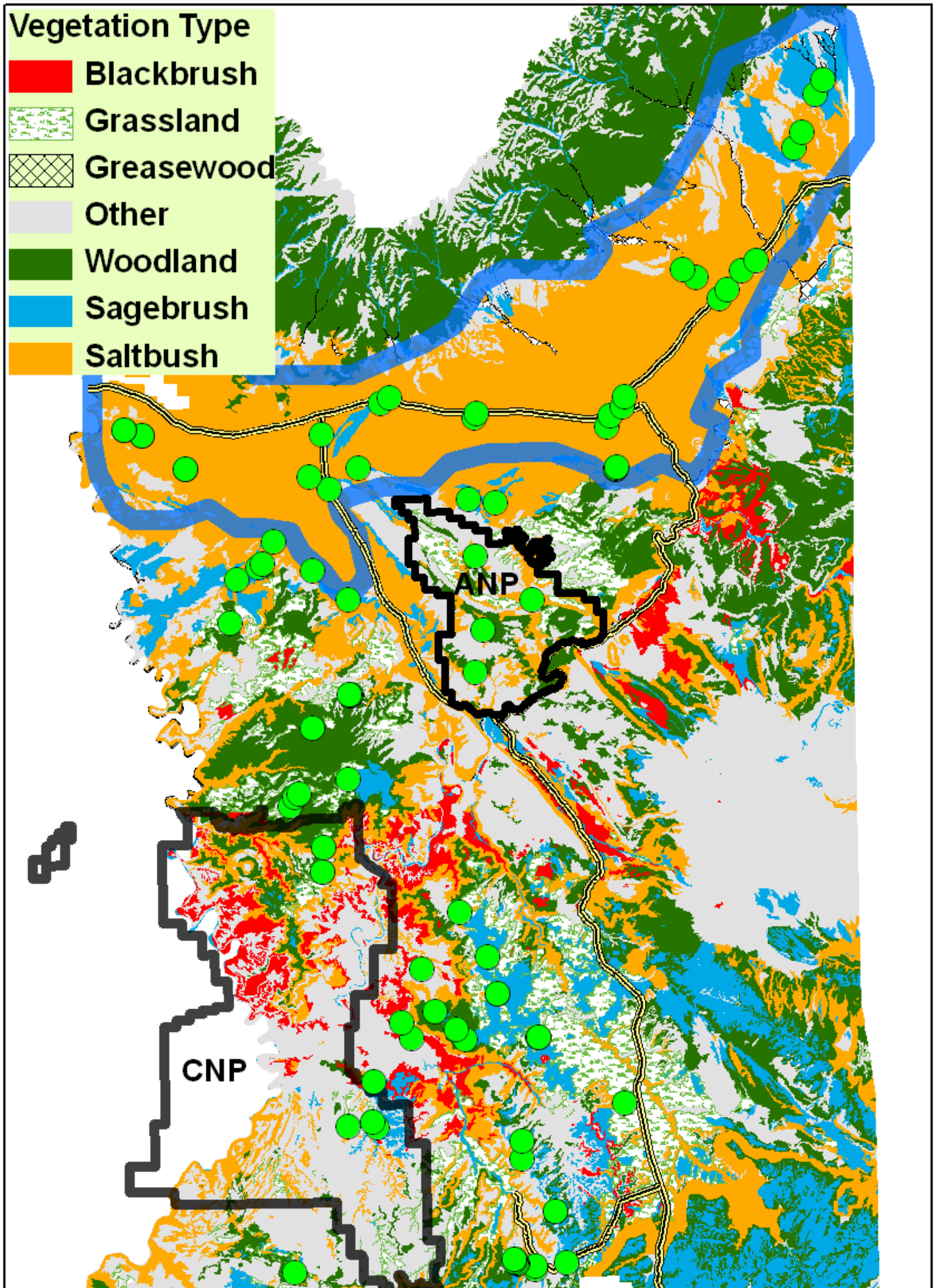


Figure 1B. Map of the study region. Area bounded by thick blue line denotes main area of soils derived from Mancos shale. Green circles signify location of study sites. Black outlines represent boundaries of Canyonlands National Park (CNP) and Arches National Park (ANP). Thick yellow line signifies major highways of the region. Map is derived from Southwest Regional Gap Analysis Project (http://fws-nmcfwru.nmsu.edu/swregap/) data set.

2.2 Meteorological Data

Meteorological data were acquired from five nearby weather stations in the Moab, Utah area. Four of the weather stations are operated by the Western Regional Climate Center (WRCC), one in the northern section of CNP ("The Neck"), one in the southern area of CNP ("Needles"), and one in Arches National Park ("Arches"). Wind data were not available for WRCC stations, wind measurements were acquired from a weather station ("Dugout Ranch") operated by the United States Geological Survey (USGS) in the southern part of CNP (http://gec.cr.usgs.gov/info/sw/clim-met/). Rainfall, temperature, and wind data for sites north of Arches National Park (ANP) were acquired from a weather station located at Canyonlands Field Airport (airport code: KCNY) which is approximately 29 kilometers northwest of Moab, UT.

Sixty-three percent of winds greater than 8 ms^{-1} occurred in the spring, 23% in the summer, and 13% in the winter during the study period. This observation appears to be typical of seasons for the past 12 years, when weather data collection first began in the area. Wind >8 ms^{-1} has tended to peak in April, May, and June during the last 12 years. Winds >8 ms^{-1} usually initiate in March, with a large jump in hours of wind >8 ms^{-1} between February (73 hours) and March (222 hours). Total hours of wind >8 ms^{-1} followed the same pattern to wind >12 ms^{-1}, with more hours of wind exceeding 8 ms^{-1} than 12 ms^{-1}. Episodes of wind that exceeded 8 ms^{-1} for 4 consecutive hours or longer were also counted as "gusty wind events" for each sampling period (Table 2). The number of gusty wind events was highest in the spring and lowest during the winter. The summer of 2009 appeared to have more high speed wind events than the other summer periods.

Table 2. Number of wind events exceeding >8ms^{-1} velocities that were at least 4, 8, or 12 consecutive hours or longer in duration. Reported per year and collection season.

Year	Season	>4 Hours	>8 Hours	>12 Hours
2008	Winter	38	16	7
	Spring	88	43	17
	Summer	33	8	3
2009	Winter	28	9	3
	Spring	76	33	15
	Summer	65	25	7
2010	Winter	12	5	3
	Spring	81	41	21
	Summer	40	13	6
2011	Winter	26	12	6
	Spring	83	50	27
	Summer	35	9	3

2.3 Sediment Flux Calculations

Sediment-flux was calculated by dividing the sample mass by the area of the BSNE opening (10cm^2) and the sampling period duration at each collection height. Sediment flux is thus reported as grams/meter^2/day (g/m^2/d). I report sediment flux additively as the sum of sediment flux at 50cm and 100cm, so as to more fairly compare values between sites that had two or three installed BSNE's.

Collectors were generally placed at a minimum of 50m away from unpaved roads and at least 1m away from any vegetative obstructions. Perennial grasses and forbs were occasionally clipped near the BSNE if they limited movement of the wind vane. Sediment samples were sometimes collected with de-ionized water if the traps were filled with water, and later freeze dried to remove the water. Samples were weighed to within 0.001g (Denver Instruments Microscale, Denver, CO). Sample collection typically occurred on March 15, July 15, and October 15 plus or minus 2 weeks, corresponding roughly with the fall-winter, spring, and summer seasons. Flux values are thus an integration of sediment captured over several months and therefore represent long-term flux rather than discrete emission events.

2.4 Physical Site-Characteristics Assessment

A line-point intercept method was used to estimate percent cover of plants, litter, biological soil crust (BSC), and other ground-cover characteristics. Methods applied here are a sub-set of “Interpreting Indicators of Rangeland Health” (Pyke et al., 2002), a comprehensive suite of techniques to measure soil and vegetation properties that enable assessment of the soil, hydrologic, and biotic stability of rangeland sites. A recent example of application of these techniques is provided by Miller et al. (2008) to assessing the stability of rangeland resources in various soil and vegetative settings. My measurements provide a “moment-in-time” snapshot of vegetation of field plots during the summer of 2009 and 2010; detection of changes in vegetation between 2008 and 2011 at the plot-level are not available. The techniques are best used for recording perennial plants, because annual plants, which are primarily invasive species, may not be present from year to year. Only a few sites had greater than 20% annuals present at time of recording, and are referred to as “invaded” or “invasive dominated” sites. Vegetation and ground-surface cover were measured with three 50-m-long transects that extended radially from each BSNE sampler during June 2009 and 2010. Point hits of bare ground, biological soil crust, plant species, rock fragments, woody debris, presence of annual plants, and plant litter were recorded at every meter along each transect. Bare ground indicates that the soil surface was not covered by crust, rocks, litter, or woody debris, and also had no overlying plants. The size of plant interspaces was measured on each transect, in as much as large canopy and basal gaps between plants may indicate higher susceptibility to wind and water erosion (Derner and Whitman, 2009). Plant gaps are grouped into four size classes: between 25-50cm (referred to as “CG25” or “BG25”, for canopy gaps and basal gaps between 25-50cm, respectively), 50-100cm (“CG50” and “BG50”), 100-200cm (“CG100” and “BG100”), and larger than 200cm (“CG200” and “BG200”). The mean canopy and basal gap sizes were also calculated by aggregating data from all transects for a site. Soil-surface stability was measured at nine points at 5-m intervals along each transect with the field-soil aggregate stability, or “slake”, test according to the methods outlined by Herrick et al. (2005). The slake test assesses wet aggregate stability of soil samples dipped in water over a short period of time. Values range from 0 to 6 and are based on the degree of soil disaggregation over a set time period. Low values indicate low soil stability and weak resistance to erosion, and higher values indicate higher stability and greater resistance to erosion.

2.5 Sediment Physical Analysis

Particle-size analysis (PSA) was performed on composite surface-soil samples collected at a depth of 0-0.5cm at 2-m intervals along each transect from 52 sites. PSA was also performed on 34 BSNE samples. All samples were prepared by first dry sieving samples down to a <2mm fraction, then digesting organic matter with 30% hydrogen peroxide and dissolving carbonates with 15% hydrochloric acid. Sodium hexa-metaphosphate was added at the end of sample preparation to prevent sediments from aggregating during analysis. Particle-size was determined using a Mastersizer 2000

(Malvern Instruments Ltd., Southborough, MA, USA) laser-light scattering analyzer. The Mastersizer 2000 measures particles between 0.05 and 2000 microns as the percent volume of the sample. The Wentworth scale was used to define particle-size classes, and the samples characterized by percent sand, silt, and clay.

2.6 Statistical Analysis

2.6.1 Sediment Flux Variation by Soil type and Elevation

The effects of landscape-scale variables were examined by using soil type (derived from sandstone and shale formations) and elevation (low and high, less than or greater than 1550m) as the main effects in a two-way analysis of variance (ANOVA) at a significance level of *alpha* = 0.05. Flux values were averaged over all sampling periods prior to comparison with ANOVA. Disturbed Mancos (“MB”) sites were not included in this ANOVA due to high heteroscedasticity of flux values, and these sites were instead compared to undisturbed Mancos sites separately with a Student’s t-test. All sediment-flux values were log-transformed [$x' = \ln(x+1)$] prior to analysis due to their non-normal distribution and lack of homogeneity in variances.

2.6.2 Temporal Sediment Flux Variation by Vegetation and Season

Temporal trends in sediment flux were examined by using season and vegetation type as the main effects in a repeated-measures ANOVA. Individual sampling period sediment-fluxes were summed across sites and aggregated into three categories corresponding to spring (March to June), summer (July to October), and winter (November to February) seasons. Data from nine of the ten four-month sampling periods (from Summer 2008 to Spring 2011) were used to keep the temporal analysis balanced (i.e., data from three sampling periods each for spring, winter, and summer).

Tukey's Honestly Significant Difference (HSD) post-hoc tests were used to compare individual vegetation types and seasons. All ANOVA's were performed using the CAR package (Fox and Weisberg 2011) in R (R Development Core Team 2010). Analysis of the interaction between soil type and dominant vegetation was not possible, as dominant plant species do not generally occur in both soil types.

2.6.3 Site Characteristics and Physical Controls on Sediment Flux

Correlations among sediment flux and quantitative site characteristics, weather variables, and soil texture were calculated using Spearman's Rho rank test. The number of wind hours per season exceeding $8ms^{-1}$, the number of gusty wind events per season, and prior season total precipitation (up to two seasons before sampling) were calculated from the closest weather station and used as weather variables for the correlations. Gusty wind events were defined as four or more consecutive hours of wind above a wind velocity of 8, 10, or $12ms^{-1}$.

2.6.4 Regression Tree Analysis of Landscape-scale and Physical Controls on Sediment Flux

The classification and regression tree method (CART) was used to build a model that explained the variance of sediment flux with both continuous and categorical variables. CART is a suitable method for analyzing complex and non-linear ecological data sets (De'eath, 2002) such as this one. Models are created by repeatedly splitting data into homogeneous clusters or "nodes" of related observations based on the predictor variables being used. CART models tend to over-fit data sets if certain precautions are not followed such as "pruning" the tree's nodes. Pruning was carried out with 10-fold cross-validation: 10% of the dataset was set aside as a “test set” and the remaining dataset was used to create the tree; the cross-validated error is then estimated by how well the training set predicts the values of the test set. Three other rules were implemented prior to model building. Minimum improvement per node split was set at 3%, and thus the minimum number of observations needed to generate a new node was set at 20 (number of observations in group/number of total observations i.e. 20/600). Minimum number of observations in a terminal node was also set to 2% of the entire data set. The final number of nodes was limited to be within one standard-error of the minimum cross-validation error, also known as the “1-SE” rule (Maindonald & Braun 2003). The “rpart” package in R (Therneau and Atkinson, 2011) was used to create the CART model. Vegetation type, season, wind speed, total hours of wind >8 ms^{-1}, total hours of wind >12 ms^{-1}, seasonal precipitation, soil texture, and physical site characteristics were used to predict sediment flux rates throughout the study period.

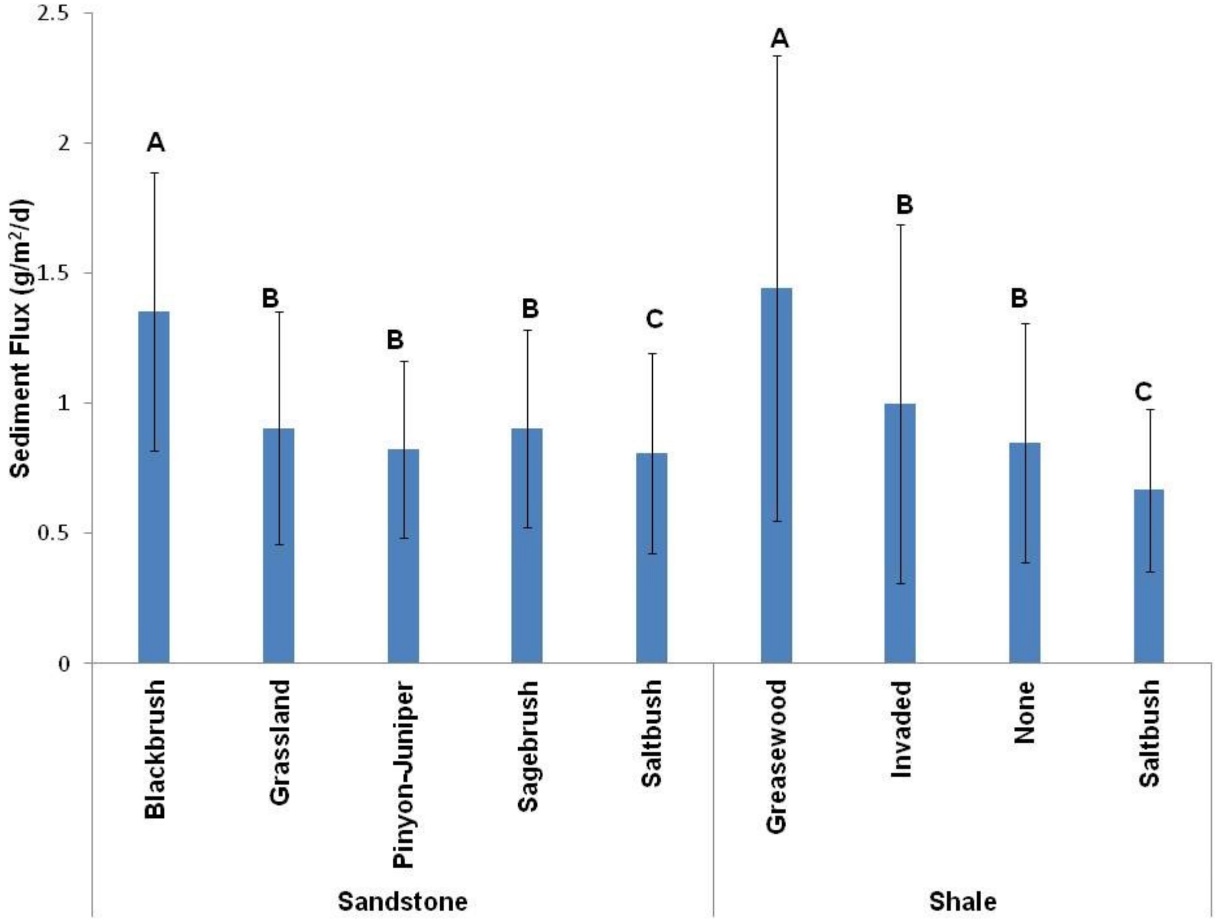
The importance of predictor variables in the CART model was assessed by using a technique known as Random Forests (RF). RF quantifies the sensitivity of a specified CART model by removing predictor variables one at a time, creating individual trees, and measuring the amount of error generated by withholding each predictor. This process is bootstrapped through a specified number of iterations until the model converges (i.e., the mean-squared error no longer decreases with new trees). A typical number of model iterations is 500 (Harper et al., 2011), and thus the RF technique cannot average the results of the iterations into a single tree. Nevertheless, the technique can be used to both rank the importance of predictor variables and quantify the amount of variance explained by the initial model. RF analysis was carried out by using the "randomForest" package in R (Liew & Wiener 2002).

3. Results

3.1 Mean Sediment-Flux by Vegetation Type, Soil Type, and Elevation

Vegetation type is an important control on sediment flux rates among sites ($F_{(7,483)} = 9.06$, $p<0.001$), with significant differences in sediment-flux among vegetation types. Figure 3 shows the mean sediment-flux separated by dominant plant species and soil type for the entire study period. Tukey's post-hoc tests indicated that greasewood and blackbrush sites had significantly higher flux than all other vegetation types throughout the entire study period, exhibiting mean rates between 9.4 ± 2.9 and 21.2 ±

Figure 3. Bar chart of log-transformed mean sediment flux by soil type and vegetation type for all sampling periods. Error bars represent standard deviation. Sites with the same letter indicate statistically similar flux rates according to the Tukey's HSD post-hoc test.



3.8 g/m^2/d (back-transformed values, p<0.001). Post-hoc tests also indicated that sagebrush, grassland, Pinyon-Juniper woodland, invaded, and BSC ("None") sites all exhibited a similar, intermediate level of sediment flux throughout the study period, and ranged between 6.1 ± 2.5 and 7.4 ± 2.5 g/m^2/d (p<0.001). Mean sediment flux was significantly lower at saltbush-dominated sites (5.1 ± 2.2 g/m^2/d, Tukey's HSD p<0.001) compared to all other sites.

Although soil type and elevation did not exert a significant effect on sediment flux, rates were significantly higher at heavily disturbed Mancos sites versus undisturbed sites ($t_{(40)}$ = 7.17, p<0.001). In general, disturbed Mancos sites exhibited the highest mean sediment flux rates across sampling periods (82.2 ± 8.7 g/m^2/d) compared to undisturbed Mancos sites (6.6 ± 2.5 g/m^2/d).

3.2 Temporal Sediment-Flux Variation

There was very large variation in flux by season ($F_{(2,482)}$ = 554, $p<0.001$). Tukey's post-hoc test showed that each season had significantly different flux rates from one another ($p<0.001$ for all seasons). Spring sampling seasons consistently had the highest mean sediment flux rates (17.98 ± 3.5 g/m^2/d) and ranged from a minimum of 3.46 g/m^2/d up to a maximum rate of 622 g/m^2/d (Figure 4). Winter had the lowest flux rates with a mean of 2.79 ± 1.77 g/m^2/d. Summer had intermediate flux values, with a mean of 7.47 ± 1.88 g/m^2/d. There was no significant interaction effect between vegetation type and season. All vegetation types appear to follow the same seasonal pattern of sediment flux throughout the entire study period. Mean sediment flux from the summer of 2008 to the spring of 2011 was 13% higher during spring 2009 than spring 2010, and 15% higher than spring 2011 across all sites (Figure 5). Sediment flux during the winter of 2011 was 51% higher than winter 2009 and 57% higher than winter 2010. Summer 2010 mean sediment flux was 27% higher than summer 2008 and 5% higher than the summer 2009. Sediment-flux across all sites did not appear to increase or decrease noticeably between sampling years.

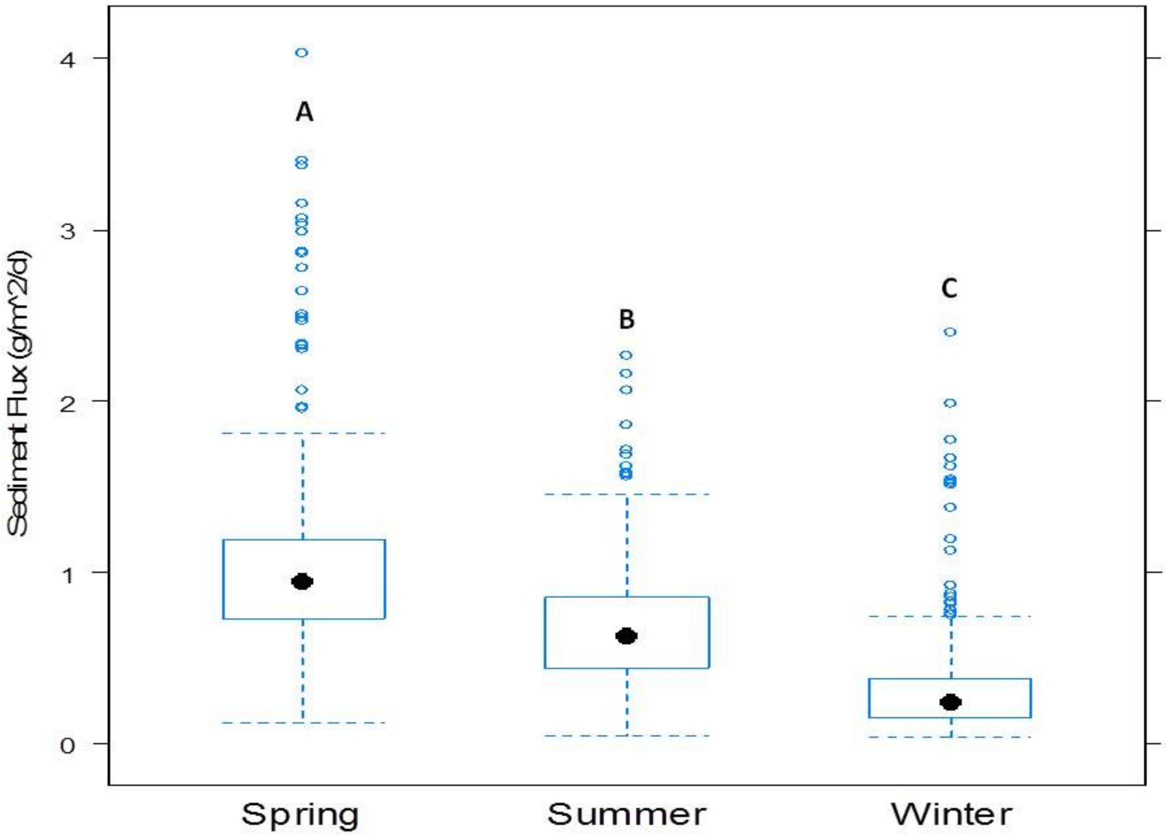
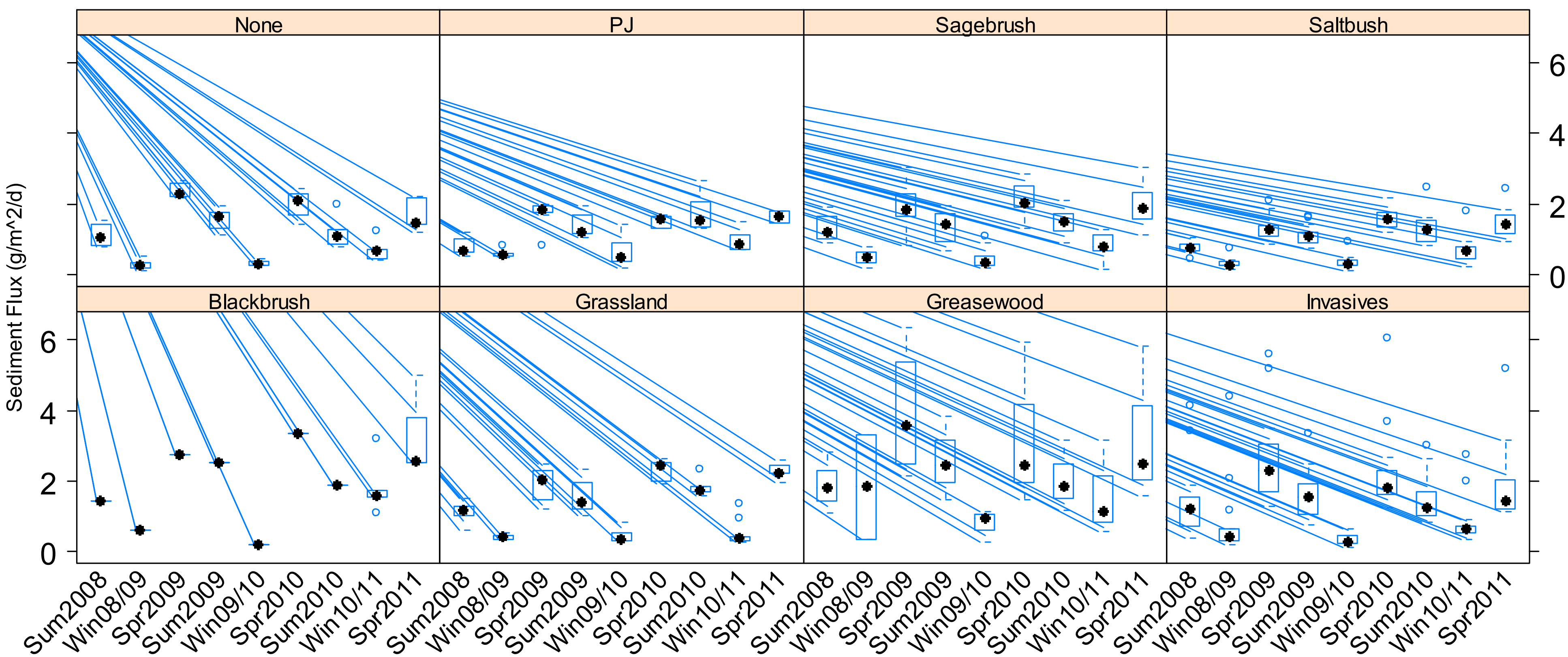


Figure 4. Box plot of log-transformed mean sediment flux by collection season. Black dots in boxes represent the median. Letters indicate statistically significant groupings according to Tukey's HSD post-hoc test.

Figure 5. Time series of (log-transformed) sampling period sediment flux by vegetation type from 2008-2011. The mean was calculated by grouping together sites of the same vegetation type.



3.3 Overall Patterns in Site Characteristics Among Vegetation Types

Several physical site characteristics varied noticeably with vegetation type. BSC cover was lower in sites dominated by invasive plants (3.31%) and higher in sites with no plant cover (81%). BSC cover was high in saltbush dominated shrublands (55%), followed by sagebrush (30%), and grass (29%) (Table 3). Bare ground was greatest in greasewood, invasive, blackbrush, and Pinyon-Juniper sites (64%, 40%, 49%, and 35% respectively), and lower in saltbush and BSC dominated sites (11% and 12%, respectively). Greasewood sites had the largest basal gaps, with a mean of 3493cm and standard deviation (SD) of 2412cm. Basal gaps were also quite large in saltbush (mean = 592cm, SD = 478), invaded (mean = 493cm, SD = 505), and woodland (mean = 394cm, SD = 367) sites. Grasslands had the smallest basal gaps (mean= 175cm, SD = 75) along with sagebrush (mean = 242cm, SD = 196) sites. Canopy-gap means followed a similar pattern to basal gap means. Perennial plant cover was highest in Pinyon-Juniper woodlands (31%), sagebrush (29%), blackbrush (26%), and grassland (26%) sites. Soil-stability values were generally higher at blackbrush (mean = 2.81, SD = 1.09) and sites dominated by biological soil crust (mean = 2.75, SD = 0.97). Soil-stability data suggests that highly disturbed Mancos sites in particular had low mean slake values (1.2, 1.5, and 1.4) compared to other Mancos sites (MB=2.2 and MC=2.5).

Table 3. Quantitative site characteristics for each vegetation type. Values are the mean of measurements recorded on three transects per study site. % Cover = total plant cover. % Annuals = annuals present. BSC = biological soil crust cover. Soil stability = slake value. Basal gap mean = mean of all basal gaps. Canopy gap mean = mean of all canopy gaps. BG indicates percent of transect within specified basal gap size class. CG indicates percent of transect within specified canopy gap size class.

Vegetation	Mean Elevation	% Cover	% Annuals	% BSC	% Bare Ground	Soil Stability	Basal Gap Mean	Canopy Gap Mean
Blackbrush	1530	25.99	0.00	14.65	49.36	2.81	283.62	170.92
Grassland	1648	25.99	1.51	29.22	22.10	2.47	175.66	132.99
Greasewood	1375	8.14	2.25	17.68	64.48	2.01	3493.07	1790.54
Invasives	1414	16.56	16.33	6.57	40.65	2.49	493.71	344.94
None	1441	10.95	0.00	81.48	11.89	2.75	4447.26	3935.28
Woodland	2063	31.18	5.73	20.27	34.99	2.50	402.80	268.41
Sagebrush	1675	29.53	7.37	30.70	24.98	2.19	242.03	196.98
Saltbush	1386	11.03	3.17	54.97	10.72	2.28	592.84	368.67
Vegetation	**BG25-50cm**	**BG50-100cm**	**BG100-200cm**	**BG>200cm**	**CG25-50cm**	**CG50-100cm**	**CG100-200cm**	**CG>200cm**
Blackbrush	0.81	2.31	7.96	45.85	5.15	8.85	14.01	46.01
Grassland	3.65	6.59	11.15	36.62	7.95	13.06	15.80	37.20
Greasewood	0.00	0.00	0.00	55.95	1.66	1.61	2.17	86.42
Invasives	0.01	0.08	0.00	7.12	2.97	6.42	9.87	64.19
None	0.00	0.10	0.00	99.88	0.00	0.00	0.21	88.84
Woodland	1.69	4.87	11.12	67.97	1.44	4.04	9.14	54.21
Sagebrush	1.62	6.20	9.49	32.26	4.32	9.63	13.56	42.97
Saltbush	0.12	0.56	2.39	59.93	1.59	4.37	12.23	70.79

3.4 Physical Site Characteristics and Sediment Flux Correlations

Percent bare ground and percent sand content in surface soil also had a noticeable positive correlation with sediment flux at all sampling heights (bare ground: $p<0.01$; sand content: $p<0.001$). Percent silt, percent clay, and soil stability all had negative correlations with sediment flux ($p<0.001$ for all) at all sampling heights. Few site characteristics have strong or significant correlations with sediment-flux as indicated by Spearman correlations among quantitative indicators of Rangeland Health, site characteristics (e.g. surface soil texture), mean seasonal peak-wind speed, and sediment flux (Table 3). Of the six quantitative rangeland health indicators, only two indicator variables (bare ground and soil stability) had a significant relation with sediment flux.

3.5 Climate Data Analysis

Hours of wind >8 ms^{-1}, temperature, and precipitation minima and maxima all occur seasonally (Figures 6A and 6B). Flux appears to be most strongly related to seasonal wind conditions, as seasonal peak wind speeds had a very strong positive correlation with sediment flux during all collection periods ($p<0.001$). Precipitation was significantly lower during the spring (13mm per month on average) than in the winter (21 mm/month) and summer (29 mm/month), but had no significant or noticeable correlation with sediment flux rates (Table 4).

Table 4. Spearman correlations between log-transformed sediment flux at three sampling heights and various site characteristics, as well as mean wind speeds per sampling season. Significant correlations are bolded. Total wind = number of hours per season that exceeded indicated wind velocity. Basal gap >200cm refers to the percentage of a transect comprised of plant basal gaps larger than 200cm, soil stability refers to the slake value, % sand, % silt, and % clay are for surface soil texture only. Note that biological crust cover % ("%BSC"), mean basal gaps, and mean canopy gaps do not significantly correlate with sediment flux. X's indicate correlation values were less than 0.01.

	Peak Wind Speed	Total Wind >8ms	Total Wind >12ms	Seasonal Precip.	Previous Season Precip.	Soil Stability	% Bare Ground
Flux-15cm	**0.63**	**0.28**	**0.23**	x	x	**-0.19**	**0.14**
Flux-50cm	**0.71**	**0.31**	**0.3**	x	x	**-0.23**	**0.17**
Flux-100cm	**0.7**	**0.34**	**0.34**	x	x	**-0.21**	**0.16**
	% BSC	**Basal Gap >200cm**	**Mean Basal Gap**	**Mean Canopy Gap**	**% Sand**	**% Silt**	**% Clay**
Flux-15cm	-0.13	0.05	0.05	-0.06	**0.24**	**-0.30**	**-0.17**
Flux-50cm	-0.14	0.09	0.06	-0.02	**0.23**	**-0.27**	**-0.19**
Flux-100cm	-0.12	0.11	0.05	-0.0	**0.27**	**-0.25**	**-0.29**

3.6 Surface-Soil Texture, Captured Sediment Texture, and Seasonality

Surface-soil texture shows some variation as a function of vegetation types (Figure 7). All vegetation types had greater than 60% sand content at the surface with the exception of Mancos sites, which had higher silt and clay content. Sand content varied between 10 and 25% by vegetation type, with the highest sand variation in Mancos sites. In general, Mancos soils showed the highest amount of variation in all categories except in silt content; silt content varied by up to 18% in grass sites. Blackbrush and saltbush had higher mean sand content (71% and 68% respectively)

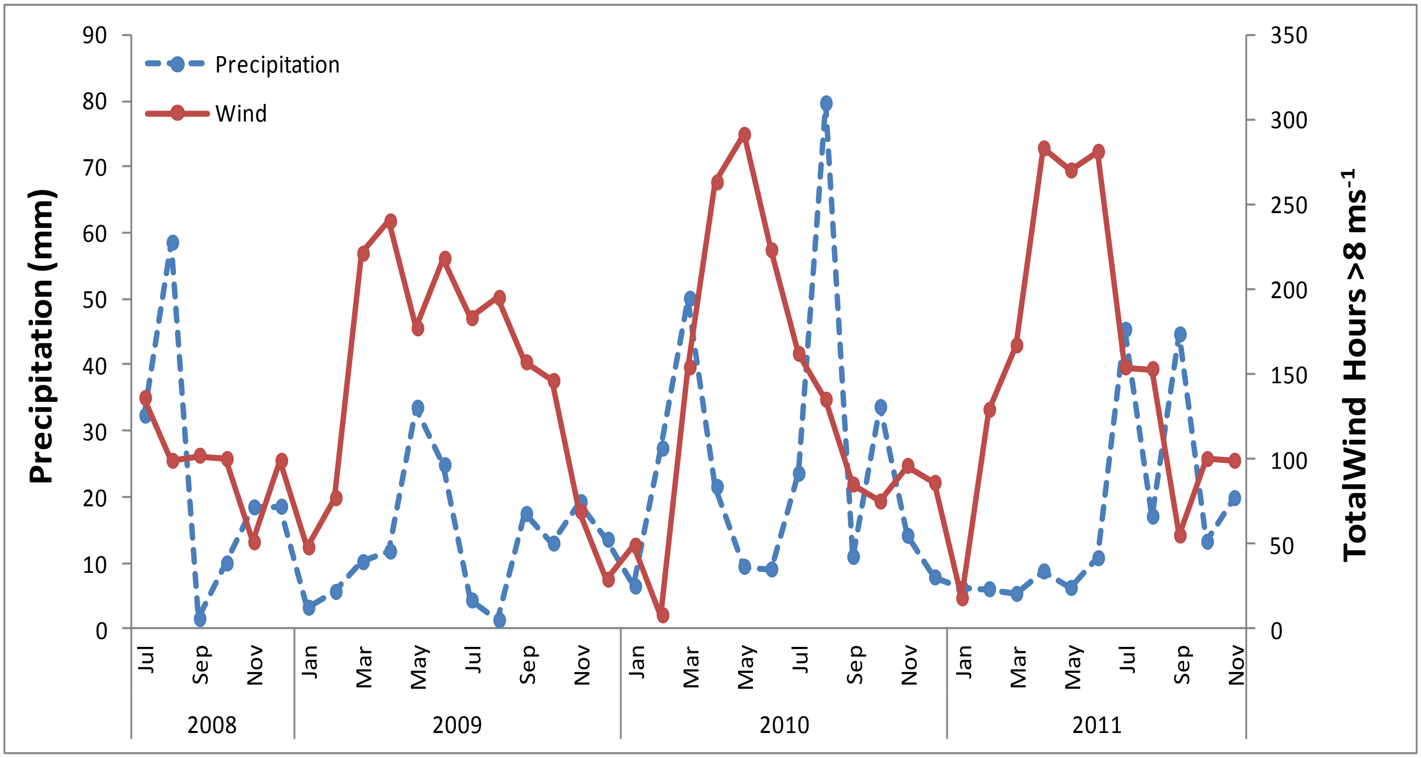
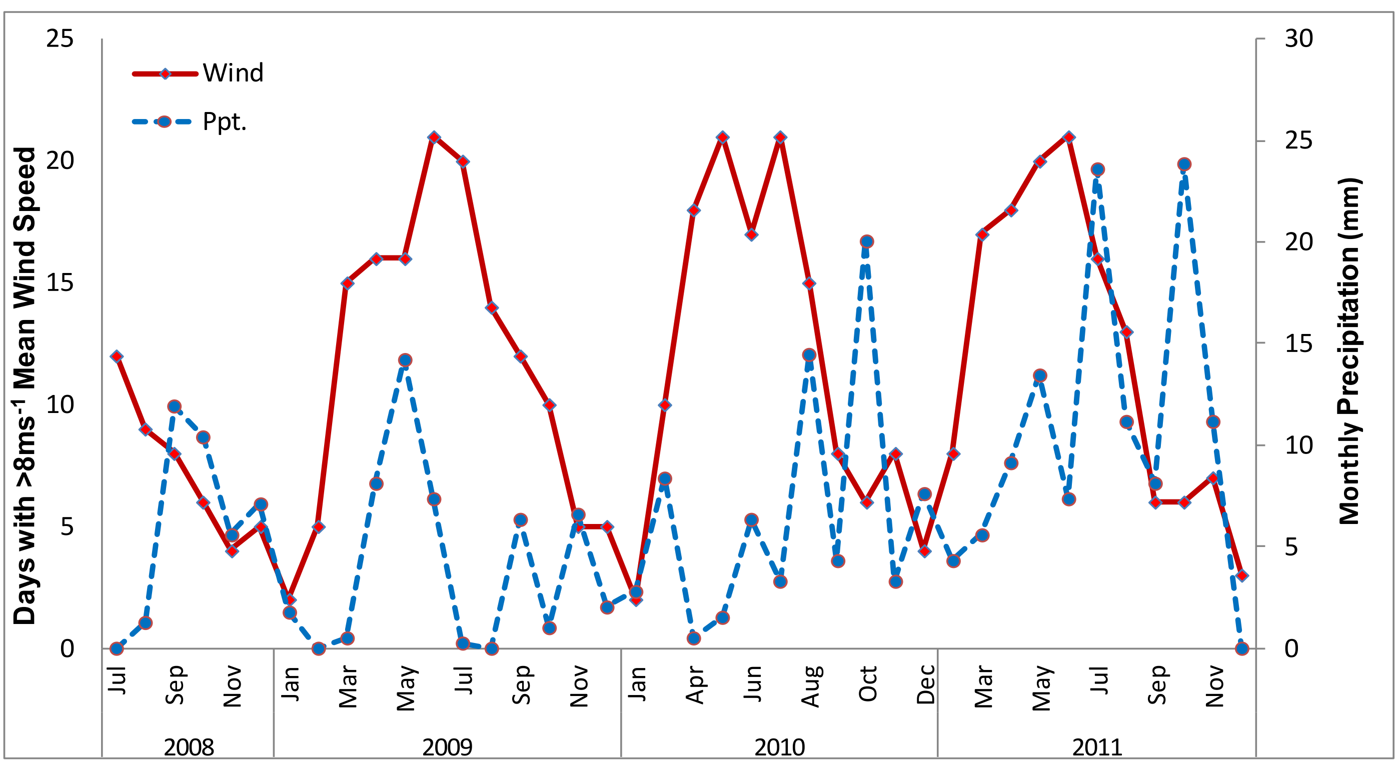


Figure 6A. Total wind hours above 8 ms^{-1} by month, and monthly precipitation at Dugout Ranch station (elevation: 1542m).

Figure 6B. Total number of days with mean wind velocity exceeding 8ms^{-1} per month, and monthly precipitation at Canyonlands Field (airport code: KCNY, elevation: 1387m).



compared to the other vegetation types. Silt content was highest in Mancos (36%) and lowest in saltbush (20%).

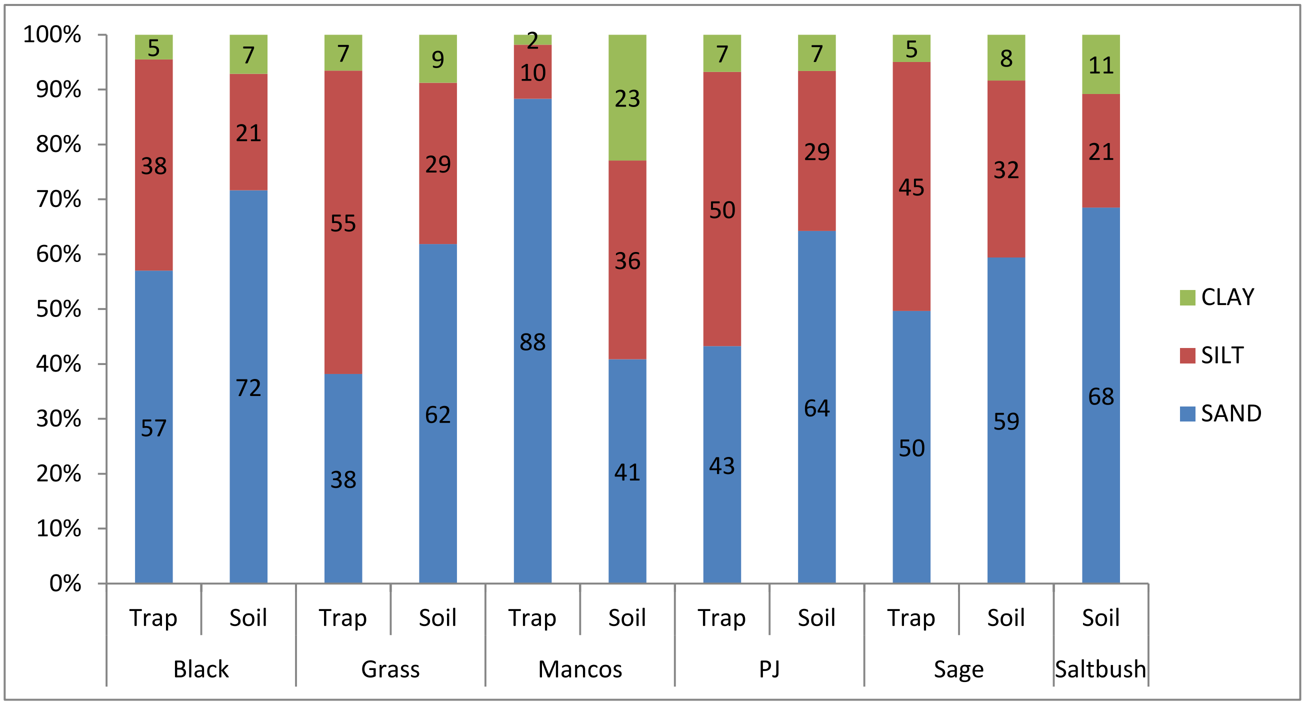


Figure 7. Surface soil and sediment trap texture by vegetation type. Only 100cm sediment trap texture is reported here.

Comparison among the 50cm, and 100cm BSNE heights, and surface soil texture revealed notable differences in sand, silt, and clay proportions. 50cm samplers tended to be enriched in sand-sized particles compared to the 100cm sampler and surface soil for all vegetation. 100cm samplers had more silt-sized particles compared to surface soil and 50cm samplers, whereas clay content was higher in surface soil compared to both the 50cm and 100cm samplers. Overall, sediment collected in the

BSNEs was more enriched in silt- and sand-sized grains when compared to local surface soil texture (Figure 7).

A subset of 12 samples from two different shrubland sites (one higher elevation sagebrush and higher elevation blackbrush) was also analyzed across three separate sampling periods. Particle size at 50cm and 100cm were analyzed for the spring, summer, and winter collections of 2010 from each site (Figure 8). Sand content of aeolian sediment sampled from the sagebrush site tended to be lowest during the spring, and highest during the winter, at both collection heights. Silt content followed a similar, inverted, pattern with high silt content during the spring and low silt content during the winter. The blackbrush site followed a different seasonal pattern. Sand content was highest during the summer at both collection heights, but varied inconsistently between the winter and spring. Silt content was high during the spring and winter, and lower during the summer at both collection heights. Clay content did not vary consistently between the two collection heights at both sites, although there was a slight increase in clay-sized particles during the spring at the sagebrush site.

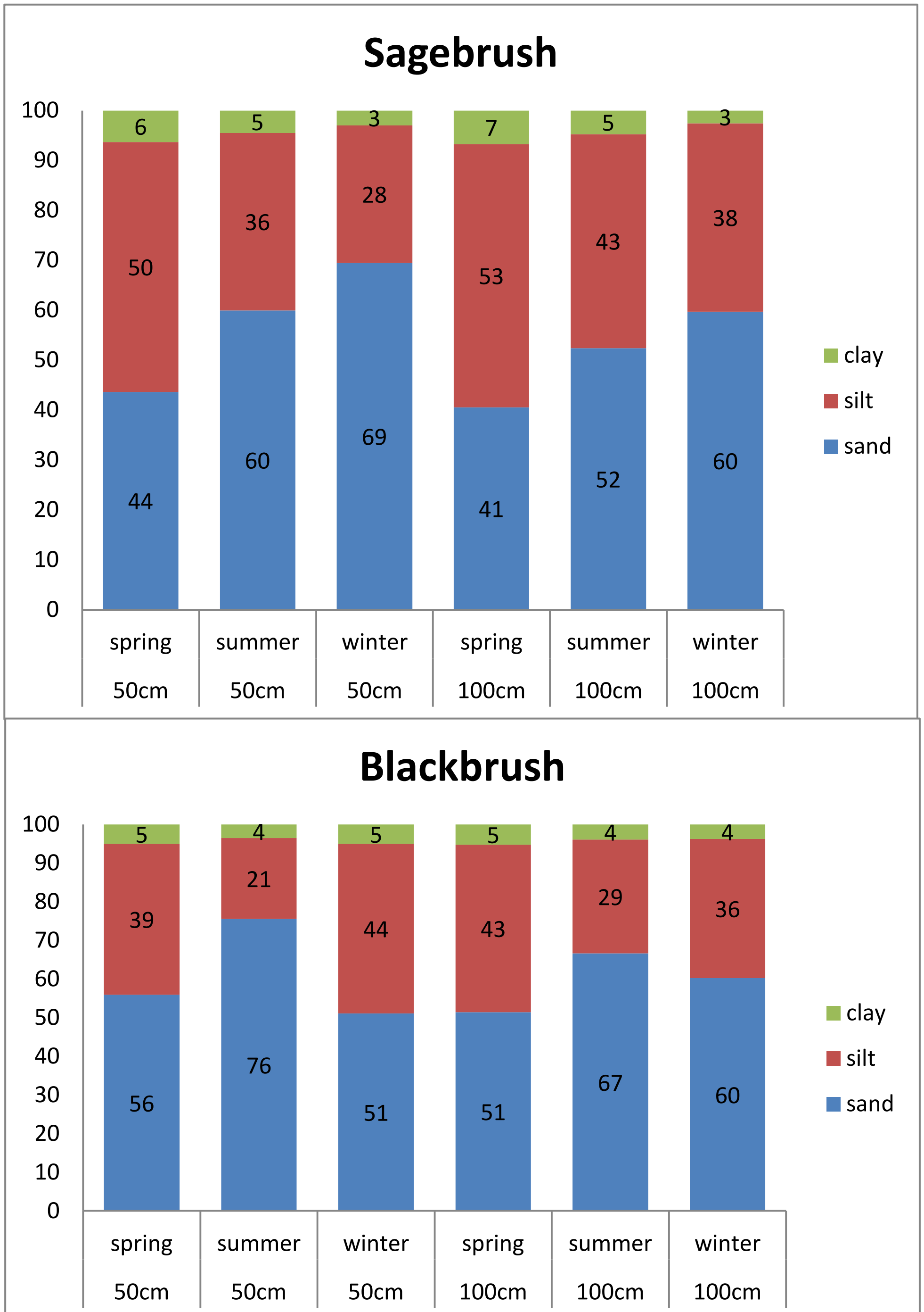


Figure 8. Sand, silt, and clay content of wind-blown sediment captured at two heights, two sites, and across three separate sampling periods. *N=12.*

3.7 Sediment Flux Controls and Regression Tree Analysis

The bootstrapped Random Forest procedure predicted 74% of the variance for combined (50cm and 100cm) sediment flux. The regression tree model included 596 of the 650 sediment flux observations throughout the study period; 54 of the samples were left out because of missing flux or rangeland health indicator values. Out of the 18 predictor variables used as input, six were included in the final model: seasonal wind hours greater than 8ms^{-1}, percent bare ground, vegetation, summer/spring, sand content, and soil stability (Figure 9A).

The single best predictor of sediment flux was the total seasonal hours of wind speed >8 ms^{-1}, followed by sand content, percent bare ground, whether season was summer or spring, vegetation type, and soil stability. The model associates relatively high flux with a wind threshold, indicating that sampling periods experiencing more than ~450 hours of wind >8 ms^{-1} typically higher sediment flux. The left branch of the tree includes less windy conditions with lower sediment flux (nodes 1-5). Sampling periods with less than approximately 300 hours of wind >8 ms^{-1} exhibited the lowest sediment flux. The absence of vegetation as a predictor variable on the left-most branches suggests that sediment flux is relatively uniform throughout all sites during low wind periods. The amount of bare ground at a site becomes important under windy conditions (total wind hours >8 ms^{-1} is between 300-450 hours). Under these conditions, sites with more bare ground have a higher mean flux. Sites with less than 67% bare ground are further split into nodes based on sand content and vegetation type. Less than 60% sand content at sites corresponds to lower flux than at sites with higher sand content. Sites with >60% sand content but low flux (node 3) are characterized by grass, sagebrush, Pinyon-Juniper, or saltbush as the dominant vegetation.

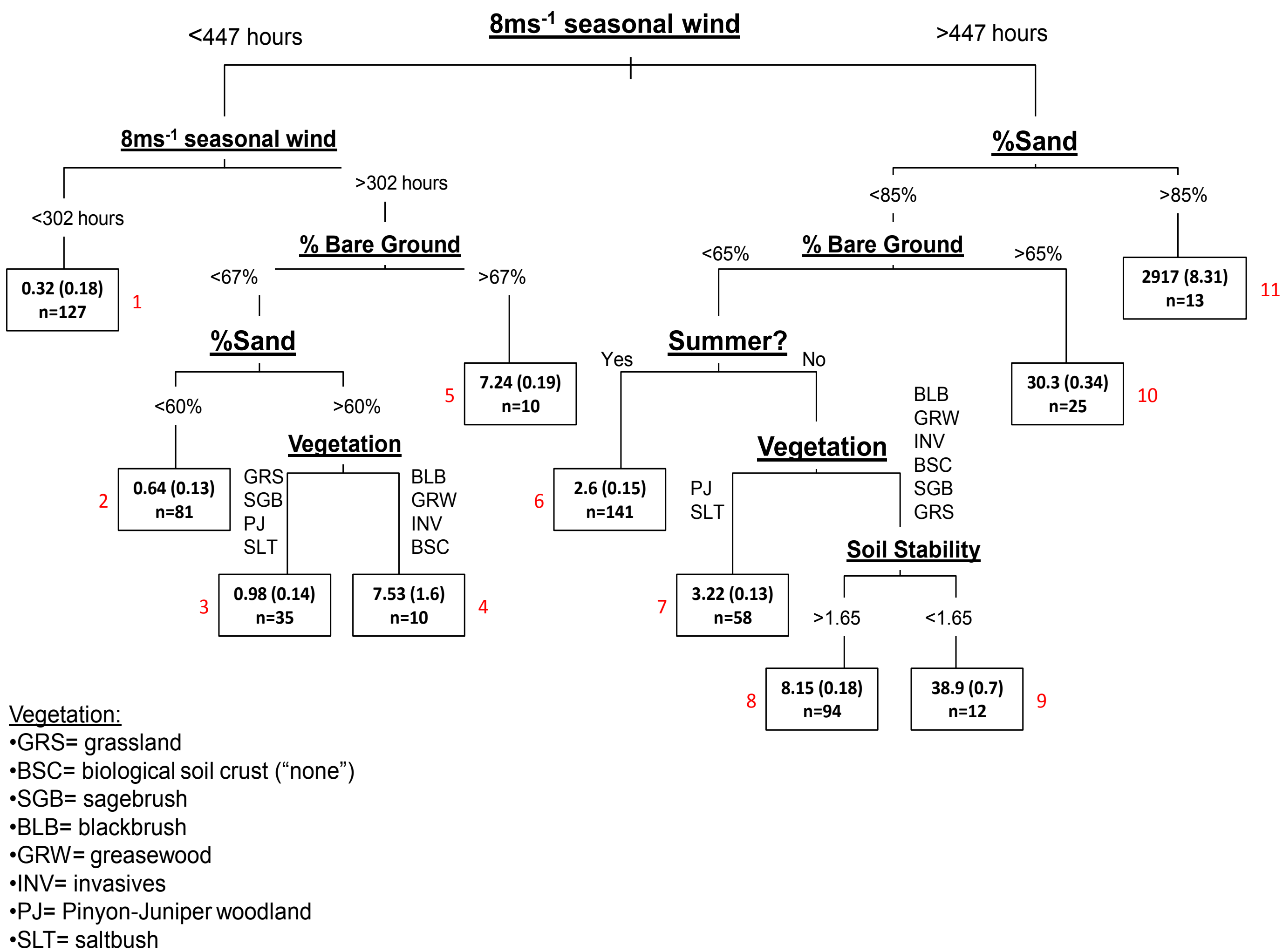


Figure 9A. Regression tree results illustrating the relationship among predictor variables and predicted sediment flux. Predictor variables are bolded and underlined; values dictating node splitting are next to or on branches. Predicted sediment fluxes are reported in boxes (as g/m^2/d), along with root-mean squared error of terminal nodes in parentheses, and the number of observations included in each node. Dominant vegetation is abbreviated next to related branches. Red numbers next to terminal nodes indicate the node ID.

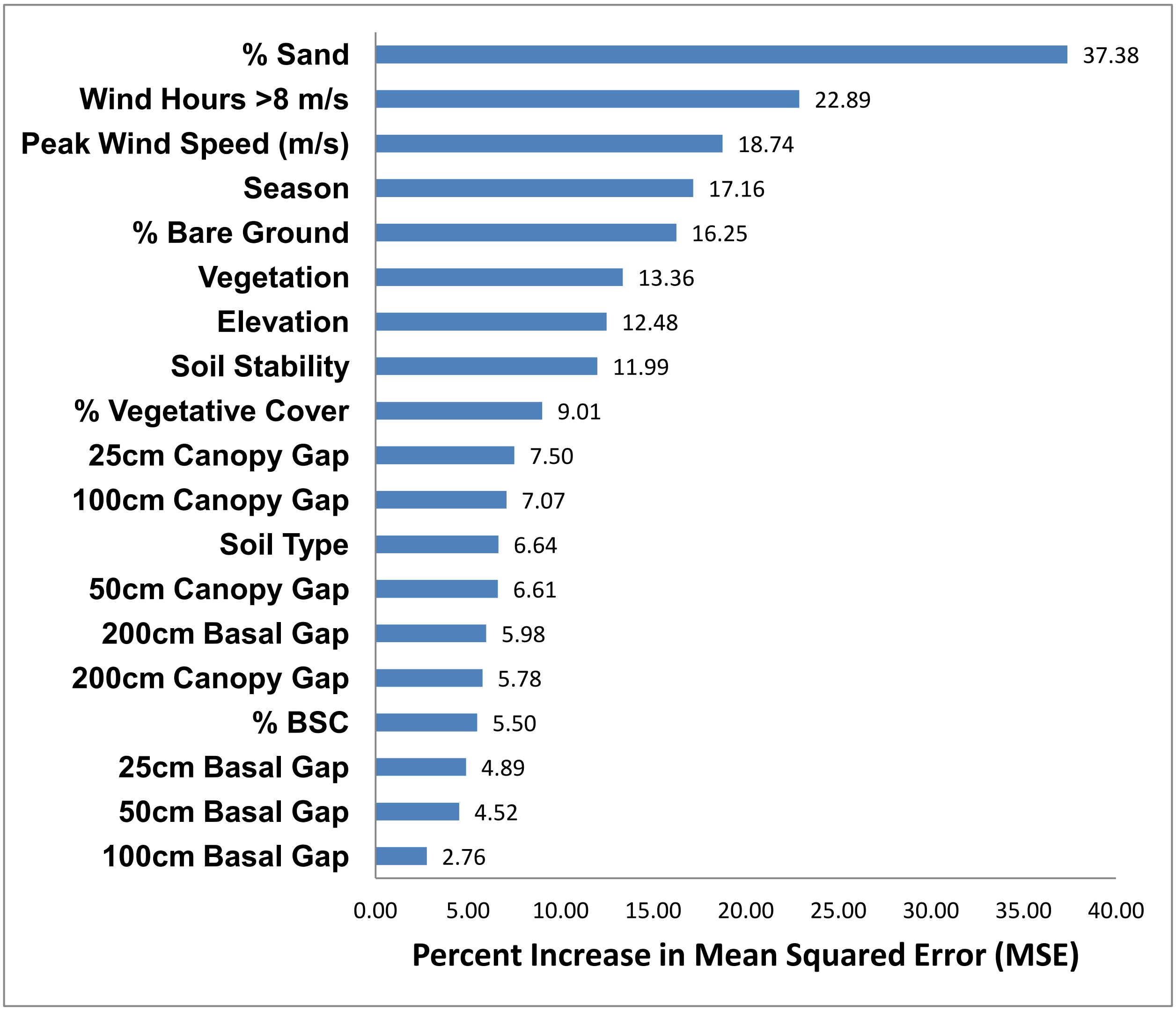


Figure 9B. Bar plot of variable importance in the regression tree. The amount of increase in mean squared error (MSE) when a variable is excluded from CART analysis is reported for individual variables. Variables with higher increases in MSE are more important to producing an accurate tree.

Sites with >60% sand content and higher sediment flux (node 4) are characterized by blackbrush, greasewood, invaded, and BSC cover but only comprise a handful of the total observations (n=10).

Higher overall sediment flux in the tree appears on the right most branches (nodes 6-11), and is a product of more hours of wind >8 ms^{-1}, high sand content, bare ground, whether summer or spring (because no winter sampling periods experienced more than 450 hours of wind >8 ms^{-1}), vegetation type, and soil stability. Most summer flux observations fall into a single node (6) that is almost directly in the middle of the tree, and also has an intermediate sediment flux value of 2.6 $g/m^2/d$. The CART results also indicate that many (combined observations of nodes 7,8, and 9, n=164) high flux observations of high flux periods occur during the spring (i.e. right branch of the “Summer” node). Nodes further down this branch also indicate that woodland and saltbush sites have a lower mean sediment flux (3.22 $g/m^2/d$) during the spring than the other vegetation types (between 8.15 and 38.9 $g/m^2/d$, at nodes 8 and 9 respectively). Extremely high mean flux (node 11) is characterized by very high sand content but occurs infrequently (n=13). Sites with soil stability less than 1.65 (node 9) have a much higher mean flux rate than sites with slake values >1.65 (node 8).

The CART and RF results appear to be mostly in agreement concerning the most important variables (according to the RF) and the best predictor variables (according to the CART) (Figure 9B); six of the seven high importance variables from the RF are included in the CART results. Surprisingly, the RF results also indicate elevation as an important predictor for sediment flux yet the regression tree leaves this variable out of the final result. Elevation fails to appear as a predictor variable in the CART results even after all tree pruning rules are relaxed (not reported here).

4. Discussion

Results here suggest that a combination of biotic, abiotic, and temporal variables exert strong controls on sediment flux. The dominant vegetation type and season had the greatest influence on how much sediment flux occurred. Vegetation type controlled sediment flux, with shrubland and invasive-dominated sites emitting significantly more sediment than other vegetation types. Strong, sustained wind events generated high overall sediment flux, and were typical of early to mid-spring. Several abiotic characteristics appeared to affect flux including higher sand content, higher incidence of bare ground, and lower surface soil stability. Two landscape-scale variables, elevation and soil type, did not exert a significant influence on sediment flux. Some evidence also suggests that flux rates are significantly higher in recently disturbed Mancos soils.

4.1 Landscape-scale Controls on Sediment Flux

The relations between vegetation type and sediment flux is complex and involves multiple factors. This complexity is particularly evident in blackbrush sites where sediment flux rates are among the highest despite also having higher soil stability and plant cover than other shrublands (Table 2). Higher soil stability and plant cover should inhibit soil erosion, but blackbrush sites are also characterized by large patches of bare ground and low BSC cover. Although soil stability was highest in blackbrush sites (mean = 2.81, Table 2), slake values below a mean of three indicate that more than 75% of soil aggregates are easily broken down, suggesting that blackbrush soils are still highly susceptible to erosion (Herrick et al. 2001). The high erosive potential of large, uncovered bare spaces and low soil stability are negated by tall plants, as exemplified by Pinyon-Juniper woodlands where flux rates are among the lowest. Plant height is an important control on soil erosion as taller plants can significantly increase the threshold wind velocity required to erode the soil surface (Okin & Gillette 2001; Okin 2006; Breshears et al. 2009). The effect of plant height on woodland sediment flux is evident in light of abundant bare ground, low soil-stability values, and relatively low BSC cover of these sites: sediment flux is consistently low despite having highly erodible surfaces. Plant height may also explain some of the large differences in flux between sagebrush and blackbrush shrublands, plant height appeared to be qualitatively higher in sagebrush sites. The influence of plant height on soil erosion is low in grasslands and BSC dominated sites, which had low sediment flux, and where shrubs and trees were rarely present. At the same time, exposed surfaces were also minimal as plant cover (perennial grasses and forbs in grassland sites) and/or biological soil crust cover were high at those sites (Table 2). The complex interaction between vegetation and soil characteristics highlights the variable influence of these many factors on sediment flux rates.

These trends are consistent with the grassland-forest continuum suggested by Breshears et al. (2009), which describes a non-linear relationship between sediment flux and woody plant cover in drylands. Grasslands occupy the lower end of the continuum, having little to no woody plant cover. The high amount of herbaceous understory cover in grasslands, though, protects the soil surface from wind erosion when woody plant cover is absent, and thus fluxes are low (Breshears et al., 2009).

Woodlands are at the high end of the continuum (high amount of woody plant cover) where flux rates are also low due to high mean plant height. Vegetation type can be a good proxy for generalizing broad trends in plant height, bare ground, and plant cover between different plant communities, and thus relative differences in sediment flux rates. Combining these general trends in vegetation with field-quantified sediment flux rates provided here may be useful for more accurately determining dust loading from southeastern Utah, and similar landscapes, in the future.

4.2 Seasonal Controls on Sediment Flux

Wind conditions play a substantial role in controlling the seasonal cycle of flux rates in all vegetation types. I found that several different measures of wind conditions all correlated well with flux patterns in the spring, winter, and summer. High sediment flux typically occurs in the early spring on this part of the Colorado Plateau (mid-March to early-April) due to onset of prolonged, and gustier, winds associated with fluctuations in the jet stream during this time of year (Shepperd et al. 2009; Urban et al. 2009). Other studies have documented high-spring flux in the Mojave and Chihuahuan deserts in particular, and related to onset of higher wind velocities (Bach et al.1996; Bergametti & Gillette 2010).

I found a strong, positive correlation between hours of wind exceeding 8 ms^{-1} and sediment flux. Several studies have reported a dramatic increase in particle mobilization above a similar wind speed threshold (Fryrear et al. 1991, 8 ms^{-1}; Whicker et al. 2002, 7 ms^{-1}). Similar studies have also found lower wind speed thresholds (Stout 2001, 4 ms^{-1}; Belnap et al. 2009, 2 ms^{-1}). Higher wind velocities are required in vegetated settings in order for saltation to occur (Shao 2001); however, wind speed thresholds vary widely due to differences in vegetation and soil characteristics (Okin et al. 2006). Other studies have found a positive correlation between hours of wind speeds exceeding 8 ms^{-1} and sediment flux (Bergametti & Gillette 2010; Reheis & Urban 2011). Sustained high wind velocities over several hours may be required for significant saltation and suspension of sediment to occur (van Donk et al., 2003). The hours of wind speeds above 8 ms^{-1} thus represents a dual wind threshold that accounts for both wind strength and erosive wind duration. While wind speed thresholds may vary substantially at the site-scale, the strong relationship between sediment flux and the 8 ms^{-1} threshold is sufficiently general to represent important conditions for the coarse spatial resolution of wind data available at such a large scale for this study.

Precipitation during and prior to sampling does not play a strong role in sediment flux patterns in southeastern Utah. In contrast, other studies have found a significant relationship between dust events and seasonal precipitation patterns (MacKinnon et al. 1990; Bach & Brazel 1996; Urban et al. 2009). The previous studies were carried out in the Sonoran and Mojave deserts, however, where annual plants are the dominant vegetation and perennials are less pervasive. Perennial vegetation is much more prevalent in Colorado Plateau landscapes, and thus response to previous seasonal precipitation is far less sensitive to precipitation variability than landscapes dominated by annual plants. Reheis and Urban (2011) found a similar lack of sensitivity to prior season precipitation in dust deposition measurements on the Colorado Plateau, reporting a weak and confounding relation between antecedent precipitation and dust-deposition rates. Multiple consecutive drought years may be necessary for perennial vegetation cover to decrease significantly and thus for sediment flux rates to respond to precipitation patterns. Moist soils tend to have higher threshold friction velocities compared to dry soils (Ravi & D'Odorico 2005), therefore the amount of precipitation during a sampling period should conceivably influence sediment flux. The coarse spatial resolution of precipitation data, as study sites could be up to fifty kilometers from the nearest weather station, may explain why precipitation, in my analyses, does not exert a noticeable effect on flux rates.

4.3 Site-scale Controls on Sediment Flux

Saltation of sand-sized particles is an important mechanism involved in the production of dust throughout the world (Shao et al. 1993; Zobeck et al. 2003) , and also at sites on the Colorado Plateau. Flux rates were higher in sandier sites across vegetation types, suggesting that sites with higher sand content may have a greater supply of readily erodible particles. The availability of large sand-sized particles can contribute to bombardment of the soil surface, weakening it by reducing roughness and breaking apart soil aggregates and thereby exposing the surface to further erosion (Belnap & Gillette 1998; Zobeck et al. 2003). Soils with higher proportional silt- and clay-sized particles tend to form stable aggregates more easily than sandy soils (Zobeck et al. 2003; Shao 2008). Sandy soils also tend to have much lower threshold friction velocities (i.e. the force required to dislodge particles from the surface) than more finely textured soils (Belnap & Gillette 1998). Sand content can therefore indicate either relative soil stability or the supply of saltating particles available for erosion, and could vary based on site conditions.

4.3.1 Physical Thresholds in Soil Erosion

Important predictors in the regression tree method may indicate non-linear physical thresholds on ecological processes (Fernandez et al. 2006; Harper et al. 2011). For example, sites with more than 65% bare ground exhibit much higher flux rates than other sites (Figure 9A). A plot of sediment flux during windy periods and percent bare ground assesses the possibility of this threshold (Figure 10A). Flux values range between approximately 0.8 and 2.8 (log-scale) up until 65% bare ground, at which level flux values appear to climb at a more rapid rate. This possible threshold is somewhat dampened by the lack of values between 75% and 85% bare ground, nevertheless there is a plethora of literature that supports the notion that removal or absence of vegetative cover leads to large increases in sediment flux (Fryrear 1993; Fryrear 1996; Gillette et al. 1997; Cahill et al. 1996; Field et al. 2012). The relation between sand content and sediment flux is also well established in wind-erosion studies (Shao et al. 1993; Cahill et al. 1996; Shao 2001). However, the sand content threshold on sediment flux appears to be less definitive than bare ground (Figure 10B), and sand content is thus more likely to be a linear relationship.

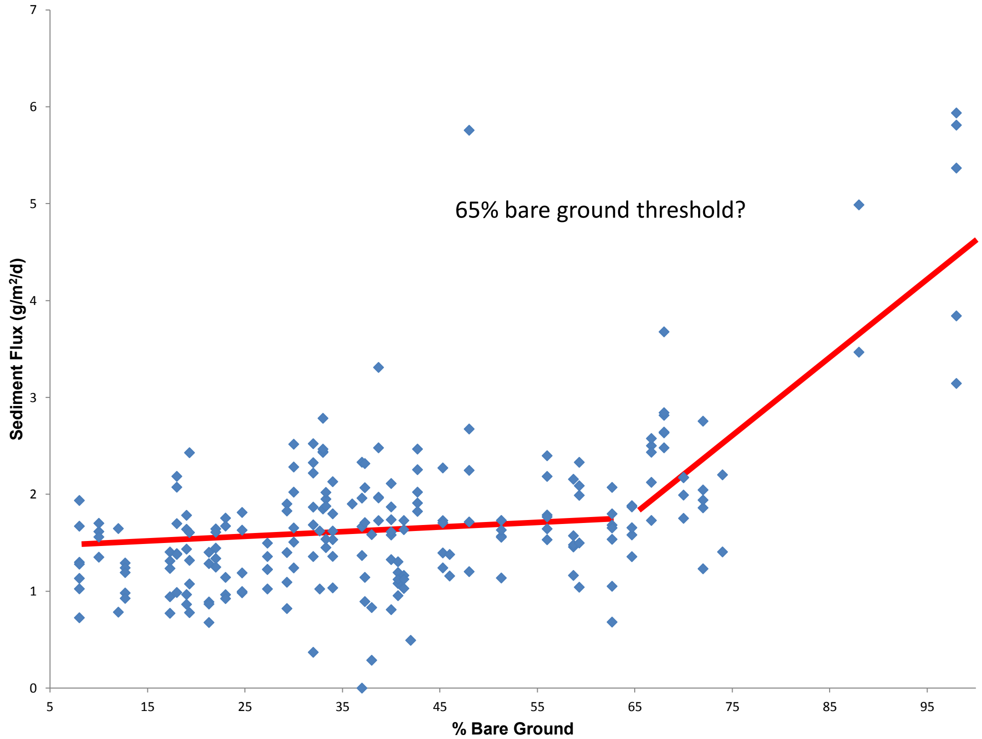
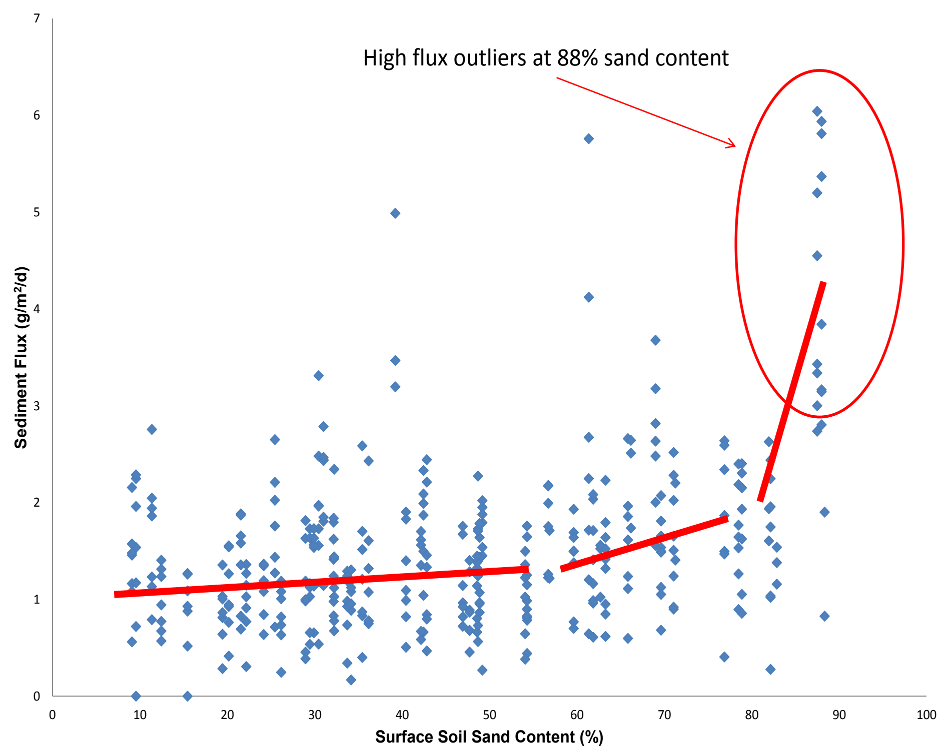


Figure 10A. Sediment flux (log-transformed) during seasons with >447 hours of wind exceeding $8ms^{-1}$ plotted against percent bare ground. Lines indicate the proposed threshold at which sediment flux begins to exponentially increase during high wind periods.

Figure 10B. Sediment flux (log-transformed) during seasons with >447 hours of wind exceeding $8ms^{-1}$ plotted against soil sand content. Lines indicate the proposed thresholds at which sediment flux begins to increase during high wind periods at 60% and 85% sand. Circle highlights high flux outliers at high sand content.



The role of biological soil crusts in stabilizing surface soils and preventing wind erosion has been studied extensively. All studies definitively conclude that BSC presence greatly enhances resistance to wind erosion but are especially sensitive to disturbance in sandy soils (Belnap & Gillette 1998; Belnap et al. 2009; Field et al. 2010; Belnap et al. 2007; Bowker et al. 2006). In this study, BSC cover was neither a significant correlate of sediment flux (Table 3), nor a significant predictor in the CART model (Figure 9A). Although the importance of BSCs in stabilizing soil surfaces is clear (Belnap & Gillette 1998; Belnap et al. 2007), many sites in this analysis had BSC cover less than 20%, suggesting that this component of wind-erosion control was absent. Sites with high BSC cover tended to have a light crust composed of cyanobacteria (not reported), rather than more developed moss and lichen crusts, which offer greater overall stability than cyanobacteria alone (Belnap & Gillette 1997). The dearth of biological soil crusts in many of these sites could also be symptomatic of historical and widespread land disturbance throughout the region.

4.4 Future Implications of Study

4.4.1 Rates Compared to Other Studies

Sediment flux patterns reported in this study are very similar to that of other dryland studies, with low sediment flux in grasslands and woodlands, comparably higher sediment flux in shrublands, and much higher sediment flux in disturbed settings (Belnap et al. 2007; Breshears et al. 2009; Belnap et al. 2009; Floyd & Gill 2011). Bergametti & Gillette (2010) carried out a study similar to this one over approximately seven years at the Jornada Long Term Ecological Research site (JER) in southern New Mexico. They reported that sites dominated by mesquite shrubs had significantly higher sediment flux than grass or other shrubland sites combined, findings supported by a previous study in the same area (Gillette & Pitchford 2004). My study found a strong relation between wind velocities and sediment flux at all types of vegetation, unlike Bergametti & Gillette (2010), who found only a strong relation between high wind velocities and high sediment flux at mesquite sites. Table 5 compares reported sediment flux rates from studies that used similar equipment to sample at a time-scale similar to the one in this study. Annual and spring sediment flux rates between the Colorado Plateau and other US dryland landscapes are similar.

Table 5. Comparison of sediment flux observed in various studies with similar equipment. Region indicates the area where the study was located. NM= New Mexico, CP=Colorado Plateau, Jornada = Jornada Experimental Range (Chihuahuan Desert). Annual and spring sediment flux are reported here to match what was recorded in other studies.

Region	Annual Flux (g/m^2/d)	Spring Flux (g/m^2/d)	Vegetation	Veg. Type	Study	Notes
CP	16	NA	perennial grass	Grassland	Belnap et al. 2010	grazing disturbance
Jornada	1.5	NA	perennial grass	Grassland	Breshears et al. 2009	
NM	27.4	NA	Mesquite	Shrub	Breshears et al. 2003	Not BSNE
NM	1.0-3.0	NA	Pinyon-Juniper	Woodland	Breshears et al. 2009	
NM	4.85	NA	perennial grass	Grassland	Breshears et al. 2009	
CP	4.2	10.6	perennial grass	Grassland	this study	100cm collection only
CP	8.8	20.5	Blackbrush	Shrub	this study	100cm collection only
CP	6.2	9.4	Sagebrush	Shrub	this study	100cm collection only
CP	5.3	4.3	Saltbush	Shrub	this study	100cm collection only
CP	114	285	Saltbush (Disturbed Mancos)	Shrub	this study	100cm collection only
CP	3.4	5.6	Pinyon-Juniper	Woodland	this study	100cm collection only
Jornada	NA	11	perennial grass	Grassland	Floyd and Gill 2011	100cm collection only
Jornada	NA	50.2	Scrape	Devegetated	Floyd and Gill 2011	100cm collection only
Jornada	NA	6	Creosote	Shrub	Floyd and Gill 2011	100cm collection only
Jornada	NA	28.4	Mesquite	Shrub	Floyd and Gill 2011	100cm collection only
Jornada	NA	6	Tarbush	Shrub	Floyd and Gill 2011	100cm collection only

4.4.2 Mancos Shale Landscapes

Sites in Mancos shale can potentially produce high amounts of dust if disturbed. While saltbush sites inhabit a large area of Mancos shale-derived soils and exhibited low flux rates, very high flux from several sites suggest this area is vulnerable to disturbance. Disturbed Mancos sites produced between 10x and 30x more sediment than undisturbed sandstone shrubland sites during the spring sampling period. Sediment flux values at disturbed Mancos sites are very high even when compared to flux values recorded during the 2002-2003 drought from a highly disturbed grassland site at Dugout Ranch (a ranch south of Canyonlands National Park). Belnap et al. (2009) reported cumulative sediment flux (the sum of sediment flux at 15, 50, and 100cm) of 5003 and 1086 g/m^2/d during 2002 and 2003, respectively, during this drought. Cumulative sediment flux at disturbed Mancos sites ranged between 2800 and 5200 g/m^2/d during the spring sampling periods from 2009-2011, exceeding sediment flux rates during a drought period at Dugout Ranch. Heavily disturbed Mancos soils can therefore produce much more sediment for multiple years compared to other disturbed sites.

Mancos soils may be particularly sensitive to disturbance due to low vegetation cover. Perennial plant cover is generally less than 20% on average across Mancos soils (Laronne and Shen, 1982), and the high sodium content of the soil makes it difficult for certain plants to access water (Carpenter and Chong, 2010). The combination of low vegetation cover and soil properties that limit plant establishment and growth suggests that disturbed Mancos soils may consistently emit high amounts of aeolian sediment before site recovery. Mancos surface soils can typically form a thin, abiotic physical crust that can be reformed in a single wetting and drying cycle (Godfrey et al., 2008). Abiotic crusting properties of Mancos soils appear to contribute more to low sediment flux in undisturbed settings than the amount of vegetative cover, which is lower compared to other sites. This is in stark contrast to the biotic control that vegetation exerts on flux rates in sandstone derived soils. Shale derived soils are a potential source of far-traveled aeolian sediments due to the higher amount of fine-particles present (i.e. silt and clay, Figure 8). Fine-particles can contribute proportionally more to regional dust loading than aerosols from sandstone-derived soils because smaller particles generally travel farther and are in suspension longer than sand-sized particles (Okin et al. 2006; Shao 2008).

4.4.3 Spatial Distribution of Vegetation and Regional Implications

There have been extensive vegetation and land-use changes on the Colorado plateau in recent years. Munson et al. (2011) documented recent changes in Colorado Plateau vegetation cover driven by increasing temperature over a 20-year period. They found significant declines of vegetation cover in low-elevation blackbrush shrublands, sagebrush shrublands, saltbush shrublands, and perennial grasslands due to increases in mean annual temperature. Changes in vegetative cover were not uniform or linear, however, with increasing blackbrush, Juniper tree (*J. osteosperma*), mormon-tea (*E. viridis*) cover, and no significant changes in Pinyon tree (*P. edibulis*) cover. Declines in perennial grass and shrub cover also appeared to be reduced in high sand content sites. The results of the aforementioned study are of particular relevance to this study because future flux will likely be more sensitive to changes in the dominant control, vegetation here. In general, declines in vegetation cover will likely lead to increases in sediment flux (Munson et al. 2010), especially in low-elevation sites where vegetation cover is low. Although elevation did not exert a significant influence on sediment flux in my study, vegetation response noted above may drive more noticeable trends at lower elevations in the future.

5. Conclusions

Vegetation type and seasonal winds are the dominant controls on dust fluxes across landscapes of southeastern Utah. Sites dominated by shrubs had higher overall flux rates than either grasslands or woodlands. Vegetation type is likely a proxy for general trends in ground cover and various plant sheltering properties. Sediment flux rates were consistently higher during the spring than summer or winter due to higher average wind speeds and prolonged wind events. Whereas sediment flux did not significantly vary between Mancos shale-derived and sandstone-derived soils, disturbed Mancos sites produced significantly more sediment than other sites indicating that disturbance effects are an important factor to consider in future studies. Quantitative variables such as high sand content, high amounts of bare ground, and low soil stability were positively related to sediment flux and control flux at a finer scale than vegetation or wind conditions, but interact in complex ways in different plant communities. Controls on sediment flux rates elucidated here are similar to other studies of wind erosion in dryland settings. Estimated flux for landscapes in southeastern Utah appear to be similar to other vegetated drylands of the western United States. Results presented here inform our current understanding of wind erosion processes in drylands by positing several landscape and site-scale controls. These results also offer the first large-scale quantification of seasonal sediment flux rates of various plant communities on the Colorado Plateau. Questions still remain regarding the variability in flux and timing of individual dust events, as opposed to the broad-scale seasonal data presented here. The impacts of resource extraction, off-road vehicle use, and grazing activities on vegetation in this area are also relatively unknown, and would likely complement data on wind erosion processes shown here.

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