Aeolian Erosion Processes in Humid Subtropical Ultisols in Southeastern United States

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Abstract

Many aeolian erosion studies have been performed in arid and semi-arid environments, while few have been performed in humid subtropical environments. Since the primary erosional factor in humid environments is precipitation, aeolian erosion is often not accounted for. This study focuses on the role of wind and wind-driven rain erosion in humid subtropical environments on an east Tennessee hill slope, USA. Three years of wind data were aggregated to weekly soil erosion measurement periods using five wind and precipitation parameters: average wind speed, peak gust, average wind direction, high wind direction, and maximum precipitation intensity. Predictive statistical regression models were generated for aeolian erosion in gully interfluves and sidewalls. Principal Components Analysis was used to develop two independent factors for wind speed and direction. Ordinary Least Square regression models for erosion on interfluves and sidewalls using the two factors and wind-driven precipitation interaction variables explained 5.9% and 15%, respectively, of variability in erosion data. A comparison of erosion on lee and stoss sidewalls indicated no significant differences in the three-year lumped dataset, but differences at the weekly time scale were significant during winter months, likely related to freeze thaw events.

Keywords: Aeolian, Erosion, Humid Subtropical, Ultisol

1 Introduction

Soil erosion is an important driver of land degradation and sediment transport. Worldwide, 432.2 million hectares (M ha) of arid lands are susceptible to aeolian erosion (Middleton and Thomas, 1997). Africa has the most land susceptible to wind erosion at 159.8 M ha, followed by Asia (153.1 M ha), Europe (38.7 M ha), North America (37.8 M ha), South America (26.9 M ha), and Australia (15.9 M ha)(Ravi et al., 2011). Four types of erosive processes dominate in soils: splash, interrill, rill, and gully erosion. The most severe form of soil erosion is gullying, where runoff water accumulates and often recurs in narrow channels, and over short time periods removes the soil to considerable depth (Soil Science Society of America, 2001). Permanent gullies are channels too deep to be easily remediated with ordinary farming equipment (Vandaele et al., 1996). Ephemeral gullies are shallow enough to be easily ameliorated, having at most a 929 cm² (1 ft²) cross section (Vandaele et al., 1996), but recur in the same place after being tilled (Poesen et al., 2003).

Gullies typically form on eroded slopes (Huo et al., 2008) where land use stresses vegetation or concentrates runoff, for example, farmland in mountainous or hilly regions. Such land uses include improper cultivation, improper use of irrigation systems, and overgrazing, but may also include urbanization and road building (Valentin et al., 2005). Gullying can also be triggered by the root systems of encroaching trees and burrowing organisms, as this increases piping in the soils (Grellier et al., 2012). Gully erosion is a common sediment producing process in a range of environments, effectively transferring sediment to valleys, permanent channels, and other areas down gradient, increasing interconnectedness of the surrounding landscape (Poesen et al., 2003).

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The development of gullies presents many problems for modern society, including but not limited to: loss of farmland and crop yields, increased labor to maintain farmland, and enhanced hillslope erosion by creating a feedback loop of erosion where the slope of gully sidewalls concentrates runoff into an area that is further incised (Valentin et al., 2005). In northern Laos, an estimated 5% of the work year is spent remediating gully erosion and in southern Israel, the hydrologic effects of gullying have rerouted flood waters necessary for agriculture, causing an 80% reduction in biomass (Valentin et al., 2005). In addition, gullies tend to increase surface runoff and reduce infiltration, which can speed up the process of aridification in arid and semi-arid areas. Sediment from gullies often ends up in water reservoirs (Valentin et al., 2005), which can be particularly problematic if gullies form on farmland or industrial lands, where fertilizers or other pollutants may be transported to waterways along with eroded soil.

Numerous studies on aeolian erosion and gully formation in desert environments have been completed (Sankey and Draut, 2014; Hagen et al., 2010; Zhang et al., 2004; Visser et al., 2004; Zhang et al., 2011; Hevia et al., 2007). In arid environments, aeolian erosion can create desert pavements when fine sediment is removed, leaving a rocky pebbled surface that protects finer sediments underneath from further erosion (McFadden et al., 1987). This process may be similar to the annealing process in gullies in the Colorado River Valley, by which the soil becomes more cohesive due to environmental heating and cooling (Sankey and Draut, 2014; Zhang et al., 2011). In the absence of precipitation, aeolian erosion and transport can occur due to saltation of larger particles or suspension of smaller particles in the air. The finest dust particles with a diameter of less than 100 μm are fully airborne, and thus promote soil build up in adjacent plots rather than contribute to erosion through abrasion when they settle. The high surface area of wind suspended sediments allows for easier nutrient transport, making them the more fertile parts of the soil. The smaller grain size enables them to travel further, and the constituent minerals are more readily available to vegetation. Suspended particles are also more likely to become surface water and air pollutants. In contrast, saltating particles alter the soil surface on impact, and the saltating particle may be broken into smaller particles that can themselves be picked up by wind and become suspended (Hagen et al., 2010). Particles between 100 μm and 840 μm saltatealong the direction of the wind, abrading the surface, and creating smaller particles in the process (Camuffo, 1995). The erodibility of soil by wind in arid environments is determined by how long the soil has remained undisturbed and the soil's protection from wind shear (Belnap and Gillette, 1997; Hagen et al., 2010). The longer the soil remains undisturbed the higher the friction threshold velocities of the soil (Belnap and Gillette, 1997).

In contrast to arid environments, rainfall in humid climates is the dominant factor contributing to erosion, where high rainfall accumulation, duration, and intensity contribute to the development of gullies on slopes (Luffman et al.; 2015, Meyer, 1981). Freeze thaw cycles have also been shown to be a significant source of erosion in gully sidewalls (Barnes et al., 2016). In these environments, swelling clays in soil may expand and contract as water is added and removed from the system, respectively. Clay particles reduce the erodibility of the soil by aggregating when wet, increasing the mass of sediment particles. Generally, the more water the clay has absorbed the larger the soil aggregates, which reduces the soil's susceptibility to erosion (Kuhn and Bryan, 2004).

The study of aeolian processes in a gully system in a humid subtropical environment presents challenges given that erosion generally occurs from rain during all seasons, and from freeze thaw cycles in the winter. Susceptibility of soils to aeolian erosion in humid climates depends largely on their texture and degree of aggregation. In silty soils, rain creates finer sediments as raindrop impacts break soil aggregates into finer, more transportable particles, and micro-aggregates are produced which are more susceptible to aeolian erosion (Yan et al., 2008). Fine grained soil particles (mostly silt-rich soil) can detach when soil cohesion is overcome by the forces of directional wind, especially when the land surface is barren (Joy et al., 2002). In contrast, wet clay rich soils exhibit greater cohesion than fine sand or silty soils, and are less susceptible to aeolian erosion (Brady and Weil, 2008) as clays act as a cementing material that holds soil particles together in aggregate (Yan et al., 2009; Kuhn and Bryan, 2004).

Wind driven rain is associated with increased erosion of cohesionless sandy soils while rain itself erodes higher amounts of finer loamy soil (Marzen et al., 2016). Wind works with rain by increasing the energy with which raindrops impact the soils (Pederson and Hasholt, 1995). The increased power of raindrop impact does not account for all of the soil dislodged, even in a wind tunnel where conditions such as temperature and humidity are controlled (Disrud and Krauss, 1971). At wind speeds of 25 miles per hour, simulated rainfall may dislodge 2.68 times more soil than simulated rain under calm conditions; a 90% mulch cover under wind driven rainfall conditions worked no better at controlling erosion than a mere 20% mulch cover under calm conditions (Lyles et al., 1974).

On hillslopes, wind driven rain increases detachment of cohesionless soil, and transports even more so than on horizontal ground; soil detachment is more pronounced at the sloped sidewall, possibly due to the influence of gravity (Marzen et al., 2016).

In arid environments, erosion and deposition dynamics in dunes are well documented with erosion occurring on the stoss side (the side facing the wind) and deposition occurring on the lee side (the side not facing the wind) (Ardon-Dryer et al., 2009). A study on the effects of wind erosion and soil properties in North China found increased sand fraction and reduced fines resulting in reduced soil fertility (Zhao et al., 2006). A similar study in New Mexico, USA, found that aeolian transport of dust from the stoss side of the slope is a major cause for the loss of soil particles and nutrients in susceptible environments (Li et al., 2007). Aeolian processes impact soil surface roughness, aggregate size distribution, and stability (Zobeck et al., 2003). Though wind driven stoss and lee effects are widely studied in arid and semi-arid dune environments, little is known about processes of erosion, transport, and deposition on lee and stoss sides in gully morphology. If the gully systems are oriented perpendicular to the dominant wind direction, lee and stoss sidewalls may be expected to experience differing rates of erosion, given that dune models show deposition primarily on the lee side and erosion primarily on the stoss side (Sloss et al., 2012; Hespet al., 2013).

A research gap exists in the study of aeolian erosion in humid environments, and this study attempts to fill that gap through the following study objectives:(i) examine the effect of aeolian processes on the formation and propagation of gully systems in a humid subtropical environment, in weathered silt and clay rich Ultisol soils; and (ii) examine differences in aeolian erosion, transport, and deposition on lee and stoss gully sidewalls.

2 Materials and Methods

2.1 Research Location

The research was conducted at the East Tennessee State University Valleybrook Outdoor Soil and Water Laboratory in Northeast Tennessee (USA) (36° 25' 21", -082° 32' 39"), located in the Valley and Ridge physiographic province (Figure 1). The Valley and Ridge province stretches along the Appalachian Mountain chain, from Alabama in the south, to New York State in the north and is composed of a series of parallel alternating topographic lows and highs with a general northeastern strike. A trellis drainage pattern dominates, characterized by short tributary streams that meet the main valley stream at approximate right angles. These short tributary streams transport gravity driven sediment away from hill slopes, which is required for gullying. On hill slopes without permanent streams, gullying is controlled by base level processes similar to those found in streams. When the gully channel is at or below base level, deposition is dominant, and when the gully channel is above base level, erosion is dominant.
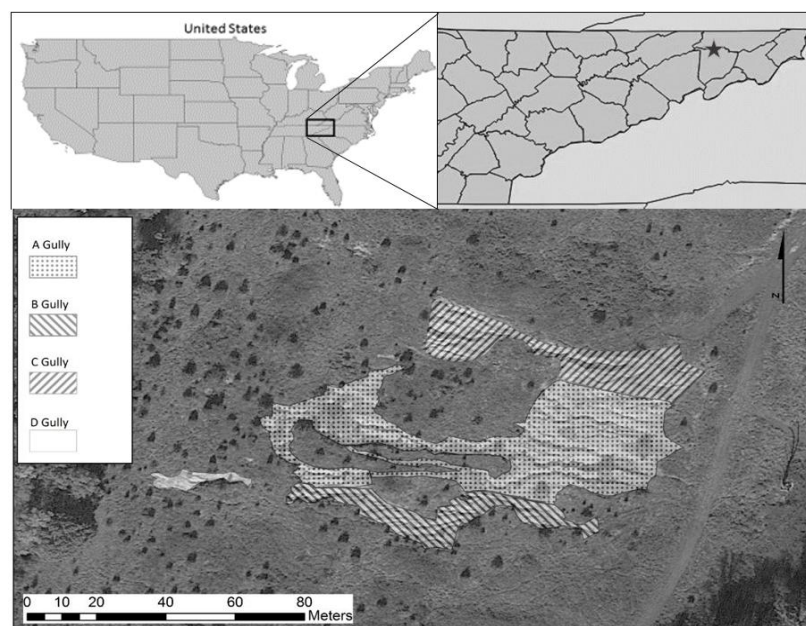

Figure 1.Valleybrook Gully System

The study was performed on an eroding hillslope on the south face of Bowser Ridge where a well-established system of gullies has grown naturally and developed into permanent gullies. Four gully systems designated A, B, C, and D (Figure 1) was investigated in the present study. In order of elevation, from lowest to highest, the A gully system is composed of the three linear gullies with elevation 522 m – 532 m, and terminates in a delta. B gully system has elevations from 525 m to 527 m, with a large dendritic gully system upstream that terminates in a narrow gully with a delta. C gully system (524 m – 531 m) is a two-gully system connected by a relatively flat, partially vegetated area. Since 2012, the uphill and downhill portions of C gully have begun to merge; the headwall of 'lower C' is in the process of eroding the delta in 'upper C'. D gully is located upslope (539 m – 544 m), and is the least well-developed of the four gully systems and sediment eroded from the D gully delta is channeled into A and B gullies. The soils at Valleybrook are Ultisols underlain by Conasauga Group carbonate bedrock. The uppermost formations, Nolichucky Shale and Maynardville Limestone, consist of shale, silty limestone, and limestone that weather into the soil on site. The valley floor is underlain by Honaker Dolomite, and the top of the ridge is an unconformable contact with Knox Group limestone (Rodgers, 1953). For soils in the gullied area the organic rich O horizon is generally absent, except on interfluves at the edge of the gully system and isolated interfluves in the interior where vegetation is present. The soil is silty clay loam for the first 8 cm, grading to silty clay at depth. These soils are well drained (USDA, 2016; Nandi and Luffman, 2012).

The gully system is part of the catchment that drains into Kendrick Creek, which receives on average 107 cm (42 in) of rain a year. Temperature ranges from an average of 1.1° C (34° F) in January to 23.3° C (74° F) in July in this humid subtropical (KöppenCfa) climate.

2.2 Field Methods

Wind, precipitation, and erosion data were collected in the field from 6/3/2012 to 6/3/2015 and processed using the workflow presented in Figure 2, outlined in the following paragraphs. An on-site Davis VantagePro 2 weather station was used to collect meteorological data including precipitation, wind speed, and wind direction over the course of the study.
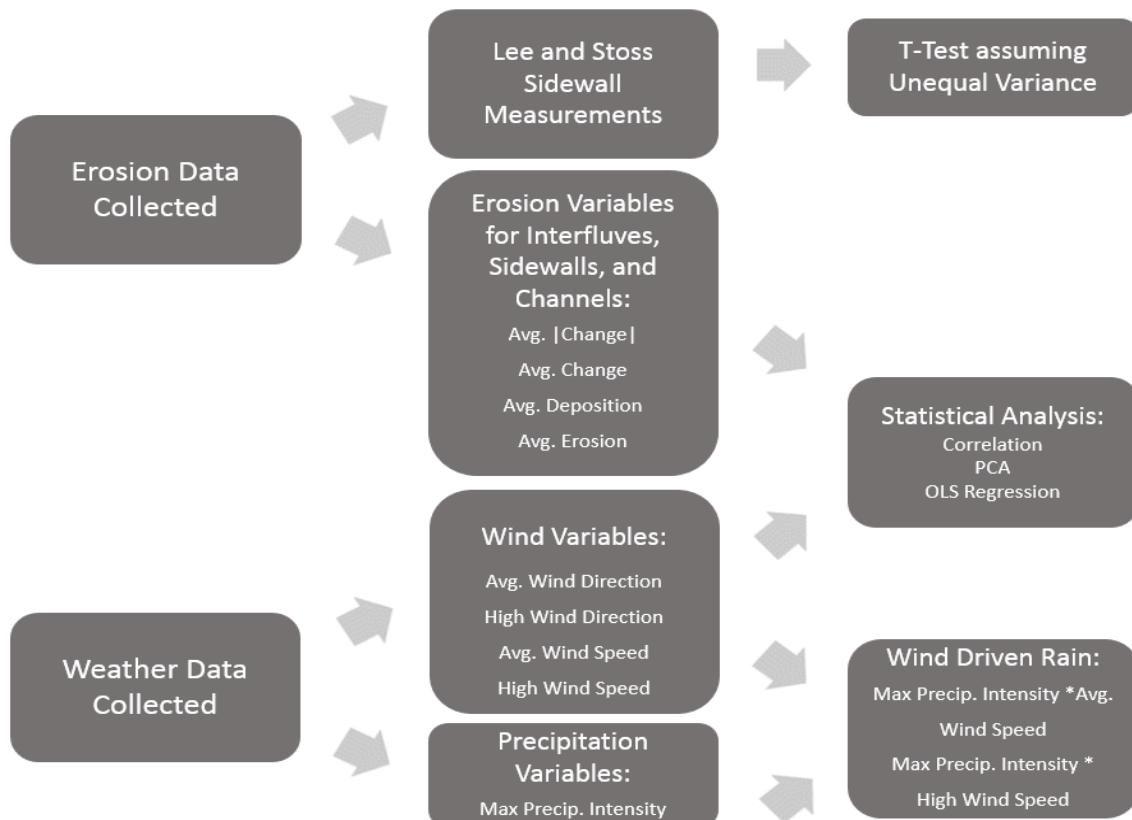

Figure 2. Workflow Diagram

2.3 Erosion Data

A total of 98 erosion pins (0.5 to 1 m long 5 mm rebar) were placed along twelve transects in the four gullies (Figure 1). Three different geomorphological settings: sidewalls, channels, and interfluves, were represented in each transect (Figure 3). Two transects were located in A gully (27 pins), three transects in B gully (23 pins), five transects in C gully (13 pins in lower C gully, and 26 pins in upper C gully), and two transects in D gully (9 pins, including three delta pins) (Figure 1). All pins were measured with a folding ruler along the longest side of each pin, from the tip of the pin to its contact with the soil. Measurements were taken weekly, and after rainfall events of at least 1.25 cm (0.5 in) in a 24-hour period.
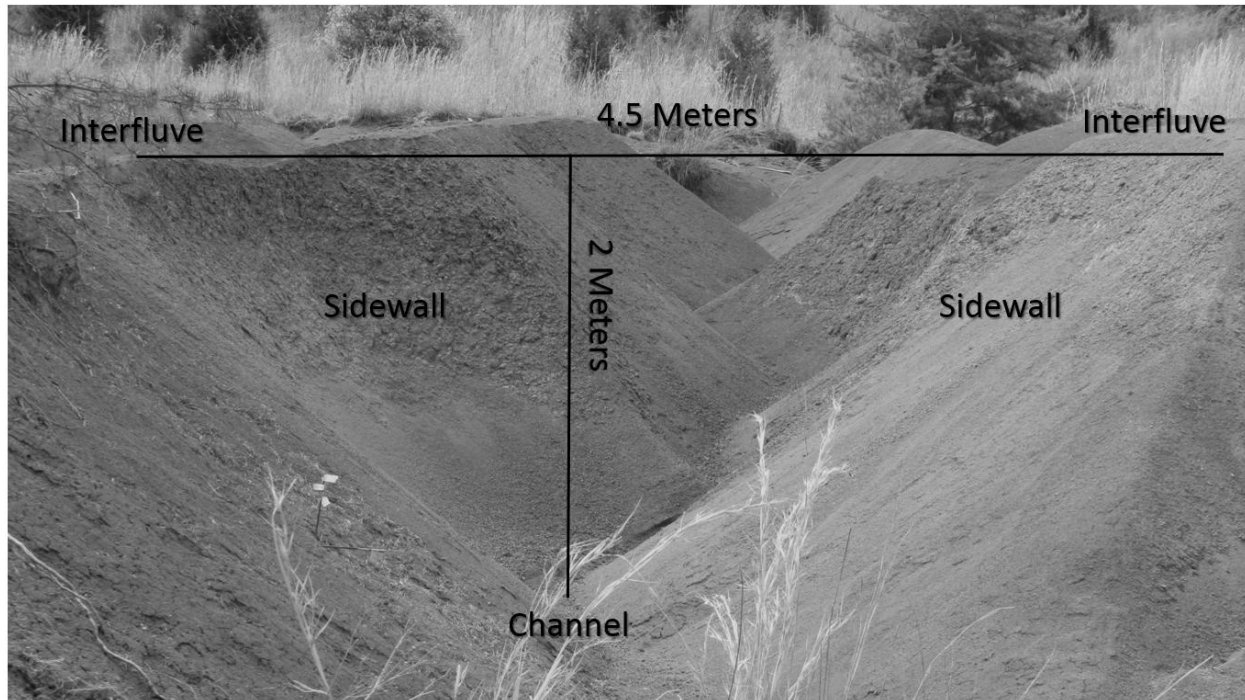

Figure 3. Gully Geomorphological Settings

Erosion was represented by twelve variables, four in each of the three geomorphic settings: interfluves, sidewalls, and channels. Erosion variables were calculated approximately weekly over the study period for the pins in each geomorphic setting: Average deposition and erosion (*Average Change*), average of the absolute value of deposition and erosion (*Average |Change|*), average of those pins experiencing net erosion(*Average Erosion*), and average of those pins experiencing net deposition (*Average Deposition*).

Average |Change| has been shown to be a useful metric for capturing change in the gully systems (Luffman et al., 2015; Barnes et al., 2016); the *Average Change* tends to be close to zero over the long term as erosion and deposition cancel each other out, however the metric may be useful to identify periods where erosion or deposition dominate.

2.4 Weather Data

Weather data were collected at five minute intervals from June 3, 2012 to June 3, 2015 using a Davis VantagePro 2 weather station located 300 meters to the north of the gully site. Four wind parameters were extracted: average wind speed (*Avg. Wind Speed*), peak gust (*High Wind Speed*), average wind direction (*Avg. Wind Direction*), and direction of the peak gust (*High Wind Direction*). Raw weather data were aggregated to the erosion measurement period, andeach wind parameter was calculated for every measurement period (approximately weekly). The mean wind speed for each period was recorded as *Avg. Wind Speed* and the peak gust during each measurement period was recorded as *High Wind Speed*. Angular wind direction was recorded as angles east and west of North (000°) with -179° to -001° denoting western directions, 001° to 179° representing eastern directions, and 180° denoting south.

To determine the average direction of the wind, angular means (ᾱ) for *Avg. Wind Direction* were calculated following Cain (1989) using:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}cos\theta_i\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n}sin\theta_i\right)^2} \qquad \text{equation 1}$$

and

$$\bar{\alpha} = arccos\left(\frac{\bar{x}}{r}\right) \qquad \text{equation 2}$$

where θ = wind direction for each measurement period *i* and n = number of measurement periods.

Rose plots of Wind Direction for each season were created with GEOrient (Holcomb, 2016). Winter months are December – February, Spring is March – May, Summer is June – August, and Autumn is September – November. To examine the impact of wind-driven rain, maximum precipitation intensity was calculated for each measurement period (*Max Precip. Intensity*). Two interaction variables were constructed: *High Wind Speed * Max Precip. Intensity* and *Avg. Wind Speed * MaxPrecip. Intensity*.

2.5 Statistical Analysis

Period-aggregated wind and precipitation intensity data and measured erosion data were assembled into a database and imported into SPSS 23 (IBM Corp., 2015). Descriptive statistics, correlation matrix scatter plots, and Spearman's rank correlation coefficients were generated for wind and erosion data. Correlation coefficients between wind parameters and erosion variables were used to select explanatory variables for regression models; multicollinearity was assessed by examining correlation among wind parameters. Principal Component Analysis (PCA) was used to generate two orthogonal components from the four wind parameters to address multicollinearity. Finally, ordinary least squares (OLS) regression models were developed for erosion variables using the components generated by PCA and the two interaction variables. For *Average |Change|* in both sidewalls and interfluves, sixOLS regression models were developed using the two components created with PCA and two interaction variables; (i) sidewall: wind components; (ii)sidewall: wind components, *Avg. Wind Speed * Max Precip. Intensity*; (iii) sidewall: wind components, *HighWind Speed * Max Precip. Intensity;*(iv) interfluve: wind components; (v) interfluve: wind components, *Avg. Wind Speed * Max Precip. Intensity*; (vi) interfluve: wind components, *High Wind Speed * Max Precip. Intensity.*

Erosion data for sidewall pins were partitioned into two groups for lee and stoss-located pins. F-tests were performed on the two data sets to compare variances, and t-tests assuming unequal variance were used to identify measurement periods with a statistically significant difference in erosion and deposition between the lee and stoss sidewalls.

3Results

3.1 Wind Data

Over the three year course of study (6/3/2012 – 6/3/2015), mean wind speed was 2.0 km/h from the southwest (196° azimuth) with average gusts of 33 km/h (201° azimuth). The wind blew primarily from the southwest across the strike of the gully system, and did not vary seasonally, as demonstrated in 5-minute interval wind direction rose plots for the three-year period of the study (n = 78,894) created in GEOrient (Figure 4) (Holcombe, 2016). The overall wind speed was low throughout the year, but wind gusts were higher in winter and spring months than in summer and fall months (Figure 5). The on-site weather station was out of service for 3 periods on the dates of April 17 - 26, 2013, September 2 - 11, 2013, and July 27 - August 6, 2014. Soil measurements were therefore not correlated to wind data for these periods, and were omitted from the study.
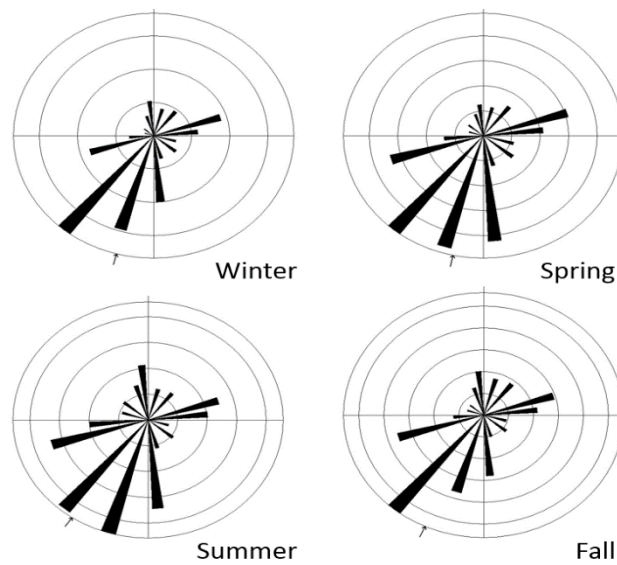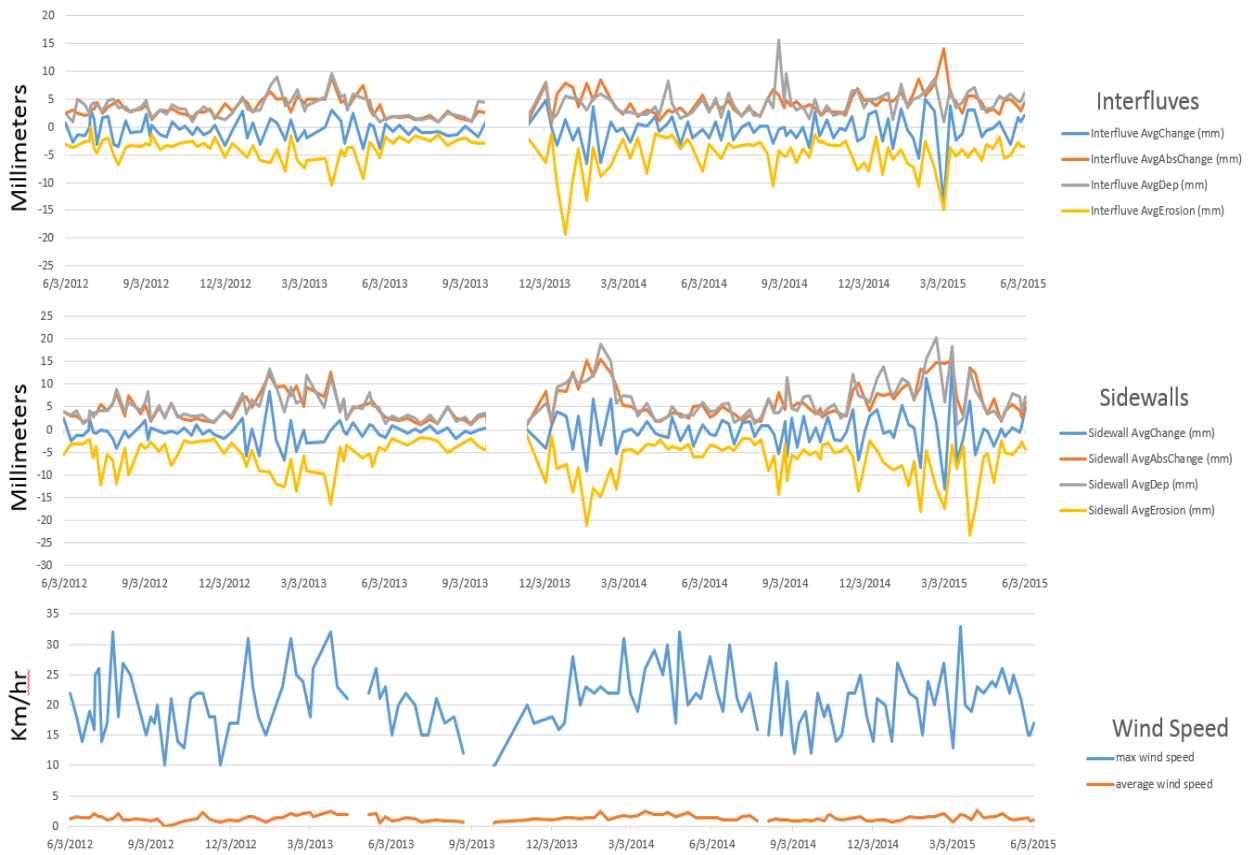
Figure 4. Wind Direction

Figure 5. Erosion, Deposition and Wind Speed

3.2 Erosion Data

The *Average |Change|* in interfluve pin length over the course of the study was 3.84 mm, and the *Average |Change|* in sidewall pin length was 5.65 mm (Table 1). A cyclic pattern in soil erosion is apparent over the three-year study. Increased erosion and deposition occur from late November to early March, and slowly tail off through May. Rates of erosion and deposition remain steady throughout the summer and fall months (Figure 5).

Table 1. Descriptive Statistics for Weather Variables and Soil Erosion Variables

	N	Minimum	Maximum	Mean	Std. Dev.
High Wind Speed (km/hr)	135	10	33	20.52	5.08
Avg. Wind Speed (km/hr)	135	0.03	2.61	1.33	0.49
Interfluve Avg. Change (mm)	135	-14	5.05	-0.499	2.43
Interfluve Avg. |Change| (mm)	135	0.56	14.11	3.84	1.99
Interfluve Avg. Deposition (mm)	135	1	15.67	3.93	2.19
Interfluve Avg. Erosion (mm)	135	-19.33	0	-4.49	2.85
Sidewall Avg. Change (mm)	135	-13.12	14.4	-0.42	3.51
Sidewall Avg. |Change| (mm)	135	0.6	15.58	5.65	3.59
Sidewall Avg. Deposition (mm)	135	1	20.2	5.84	3.85
Sidewall Avg. Erosion (mm)	135	-23.25	-1	-6.37	4.31
Max Precip. Intensity (mm/min)	135	0	101.4	73.5	15.9

3.3 Correlation

Matrix scatter plots of independent and dependent variable pairs are non-linear; hence nonparametric Spearman's rho correlation coefficients were calculated (Table 2). For sidewalls, a statistically significant correlation exists between *Average |Change|* and the two wind variables *High Wind Speed* (r = 0.304, p = 0.01) and *Avg. Wind Speed* (r = 0.215, p = 0.05). For interfluves, significant correlation exists between Average *|Change|* and the two wind variables *High Wind Speed* (r = 0.269, p = 0.05) and *Avg. Wind Speed* (r = 0.206, p = 0.05). The remaining erosion parameters (*Average Change, Average Erosion, Average Deposition*) were not as strongly correlated with wind parameters and have previously been shown to be less effective variables to model erosion at this site (Luffman et al., 2015). Therefore, they were excluded from further modeling. Erosion in gully channels was not significantly correlated to wind parameters and was therefore also excluded from further modeling.

Table 2. Spearman's Rho Correlation for Wind Variables

	High Wind Speed	Avg. Wind Speed	Avg. Wind Direction	High Wind Direction
High Wind Speed				
Avg. Wind Speed	0.579**			
Avg. Wind Direction	0.317**	-0.254*		
High Wind Direction	-	-	0.799**	
Sidewall Avg. |Change|	0.304**	0.215*	-	-
Sidewall Avg. Deposition (mm)	0.248**	-	-	-
Sidewall Avg. Erosion (mm)	-0.242**	-	-	-
Interfluve Avg. Change (mm)	0.175*	-	-	-
Interfluve Avg. |Change| (mm)	0.269*	0.206*	-	-
Interfluve Avg. Deposition (mm)	0.242*	0.222*	-	-
Interfluve Avg. Erosion (mm)	-0.195*	-	-	-

* significant at p = 0.05, ** significant at p = 0.01

3.4 Principal Component Analysis

Two components with eigenvalues greater than 1 explained 89% of the variability in wind speed, and 96% of the variability in wind direction.

Orthogonal Varimax Rotation generated two components that loaded high on wind direction (Component 1) and two components that loaded high on wind speed (Component 2). Two components used in the OLS regression model were therefore:

*Wind Direction = -0.166 (High Wind Speed) + 0.087 (Avg. Wind Speed)+ 0.957 (Wind Direction) + 0.963 (High Wind Direction)*and*Wind Speed = 0.896 (High Wind Speed)+ 0.887 (Avg. Wind Speed)– 0.112 (Wind Direction)+ 0.033 (High Wind Direction).*

3.5 Regression Models

The Ordinary Leas Squares (OLS) regression model for erosion in interfluves using the two wind components (model (i)) explains 5.2% of variability ($R^2 = 0.052$, $p = 0.011$). The addition of the interaction variable *Avg. Wind Speed * Max Precip. Intensity* (model (ii)) increased the explanatory power of the model ($R^2 = 0.059$, $p = 0.004$), however only the wind speed component and the interaction variables were retained. In model (iii) using the two wind components and the second interaction variable, *High Wind Speed * Max Precip. Intensity*, only the *Wind Speed* component was retained, and explained 4% of variability in the *Average |Change|* ($R^2 = 0.04$, $p = 0.000$)(Table 3).

For sidewalls, OLS regression models of *Average |Change|* show that the wind speed component solely (model (iv)) can explain 7.9% of variability ($R^2 = 0.079$, $p = 0.000$), however when the interaction variable *Avg. Wind Speed * Max Precip. Intensity* was added (model (v)), 15% of variability was explained ($R^2 = 0.15$, $p = 0.000$).Replacing the interaction variable with *High Wind Speed * MaxPrecip. Intensity* in model (vi) reduced the explanatory power of the model ($R^2 = 0.132$, $p = 0.000$). Coefficients for all interaction variables were negative in all OLS models (Table 3).

Table 3. OLS Regression Using PCA Factors and Interaction Variables.

Dependent Variable	Independent Variables	Model	Adjusted R²
	Wind Direction; Wind Speed; Avg. Wind Speed*Max Precip. Intensity	= 5.177 + 0.720 (*Wind Speed*) - 0.014 (*Avg. Wind Speed*Max Precip. Intensity*)	0.059
Interfluve Avg. |Change|	Wind Direction; Wind Speed	= 3.841 + 0.355 (*Wind Direction*) + 0.385 (*Wind Speed*)	0.052
	Wind Direction; Wind Speed; High Wind Speed*Max Precip. Intensity	= 4.884 + 0.519 (*Wind Speed*)	0.04
	Wind Direction; Wind Speed; Avg. Wind Speed*Max Precip. Intensity	= 9.347 + 2.129 (*Wind Speed*) - 0.039 (*Avg. Wind Speed*Max Precip. Intensity*)	0.15
Sidewall Avg. |Change|	Wind Direction; Wind Speed; High Wind Speed*Max Precip. Intensity	= 9.184 + 1.69 (*Wind Speed*) - 0.002 (*High Wind Sped*Max Precip. Intensity*)	0.132
	Wind Direction; Wind Speed	= 5.581 + 1.044 (*Wind Speed*)	0.079

3.6 Stoss and Lee Effects

Since the dominant wind direction is approximately perpendicular to the strike of the gullies, erosion on stoss and lee sidewalls was compared. Statistically significant differences between erosion on stoss and lee slopes were found in 12 of 135 (9%) weekly measurement periods ($p \leq 0.05$) (Table 4) which is close to the number one might expect by chance at this level of significance. Six (50%) of these periods follow the expected patterns of stoss side erosion and lee side deposition. When only Fall and Winter months are considered, 9 of 68 (13%) weekly measurement periods show a significant difference ($p < 0.05$) in erosion between lee and stoss sidewalls, and 3 (33%) of these follow the expected pattern of stoss-side erosion and lee-side deposition.

4 Discussions

Gullying is present throughout the Appalachian mountain chain, and has a significant impact on available land for farming, industrial lands, and slope stability. In addition, gullying has impacts on water quality as eroded sediment delivers excess nitrogen and other pollutants to surface water of the Appalachians. The dominant method of gully erosion in humid environments is precipitation, while erosion is primarily aeolian in arid environments (Visseret al., 2004; Zhang et al., 2011). In both environments, aeolian processes mobilize the fine sediment and precipitation runoff transports them downstream.

This study agrees, showing that both wind speed and direction accounts for a small but significant proportion of soil erosion in humid subtropical environments. The observed 5.2% of *Average |Change|* in interfluves, and 7.9% of *Average |Change|* in sidewalls explained solely by wind parameters agrees with expected values in humid subtropical environments (Zhang et al., 2004), but is not as high as is expected in arid environments (Belnap and Gillet, 1997; Sankey and Draut, 2014; Visser et al., 2004; Zhang et al., 2011). Since the primary wind direction is orthogonal to gully strike, wind does not play a large role in channel erosion and deposition.

The low R² values from the OLS models are likely due to high clay content in Ultisol soils in the research site. Clay particles reduce the erodibility of the soil by aggregating when wet, increasing the mass of sediment particles (Kuhn and Bryan, 2004) and require a higher wind speed to mobilize (Camuffo, 1995; Hagen et al., 2010). This study measured the incremental effect of wind on gully erosion in areas largely dominated by precipitation and freeze thaw (quantified in prior studies), and therefore lower model explanatory power is to be expected. Two prior studies performed at Valleybrook show that precipitation and freeze-thaw cycles explain much of the erosion at this site. Precipitation accounts for around 50% of erosion and primarily affects the gully channels, while freeze-thaw accounts for 27% of erosion, where it primarily affects the sidewalls (Luffman et al., 2015; Barnes et al., 2016).

Interaction variables (*Avg. Wind Speed * MaxPrecip. Intensity* and *HighWind Speed * Max Precip. Intensity*) included accounting for wind driven rain had negative coefficients, indicating that when high winds and high precipitation intensity occurred simultaneously, less erosion occurred in interfluves and sidewalls. This was likely due to the cohesive clay rich soil which binds when wet, increasing the size of aggregates, thus making them less susceptible to wind erosion (Kuhn and Bryan, 2004). These results suggest that wind erosion may be examined independently of rain variables, and agree with Luffman et al. (2015) who found that precipitation related erosion in this gully system is driven by precipitation accumulation and duration, not intensity. This study adds to the previous work by quantifying the incremental effect of aeolian processes on erosion at this site.

Erosion is expected to be the dominant process on the stoss sidewalls, while deposition is expected to dominate the lee sidewalls. In the 12 measurement periods with a statistically significant (p < 0.05) difference in lee and stoss erosion over the three years of the study, this pattern only emerges in 6 measurement periods. We propose the following explanation: since the lee sidewalls are north-facing, stoss and lee effects may be masked by freeze thaw effects and formation of needle ice that persists during the day on lee sidewalls due to deep shadows during winter months. Stoss sidewalls may experience increased freeze thaw cycles due to higher daytime direct sunlight. This suggests that slope aspect may play a larger role in erosion than stoss and lee effects.

Factors outside the control of the researchers may also influence results. Deer, wolf, and turkey tracks have been observed in the gully system and animal tracks have been documented around the study area. Burrows for ground nesting bees have been observed on gully sidewalls, though not in close proximity to erosion pins. These factors may influence erosion rates around pins where they have been observed.

5 Conclusions

This study examines the effects of aeolian erosion on gullies in a humid subtropical environment in silty clay-rich soils. Gullies typically form in hilly and mountainous regions, and studies of wind's effect on gullying have previously focused on arid environments with silty soils. A natural gully system on an East Tennessee (USA) hillslope was monitored for three years, and a statistical model was built using the parameters *Avg. Wind Speed, High Wind Speed, Avg. Wind Direction,* and *High Wind Direction* as the explanatory variables, and the erosion variable *Average |Change|* in interfluves and sidewalls as the dependent variables. Two components were extracted using PCA, one loading high on wind speed and the other loading high on wind direction. These components were used as explanatory variables in an OLS regression model. For interfluves, 5.2% of *Average |Change|* was explained by the regression model using wind components. Similarly,7.9% of *Average |Change|* in sidewall erosion was explained by wind components. Inclusion of interaction variables between wind speed and precipitation intensity increased the explanatory powers of the models for both interfluve (R² = 0.059) and sidewall erosion (R² = 0.15). The negative value of the interaction coefficients for all models indicates that precipitation plays a more important role in the formation of clay aggregates than in causing erosion by wind-driven rain. T-tests determined that wind direction played a significant role in differential erosion rates on lee and stoss sidewalls during a limited number of measurement periods, but this was heavily weighted towards winter months when needle ice regularly forms, suggesting that slope aspect and freeze thaw processes play a larger role than wind. These results illustrate the small but significant incremental effects of aeolianerosion in interfluves and sidewalls of gullies in Ultisol soils in humid subtropical environments.

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