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Gully morphology, hillslope erosion, and precipitation characteristics in the Appalachian Valley and Ridge province, southeastern USA

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ABSTRACT

This study investigates gully erosion on an east Tennessee hillslope in a humid subtropical climate. The study area is deeply gullied in Ultisols (Acrisol, according to the World Reference Base for Soil), with thirty years of undisturbed erosional history with no efforts to correct or halt the erosion. The objectives are (1) to examine how different gully morphologies (channel, sidewall, and interfluve) behave in response to precipitation-driven erosion, and (2) to identify an appropriate temporal scale at which precipitation-driven erosion can be measured to improve soil loss prediction. Precipitation parameters (total accumulation, duration, average intensity, maximum intensity) extracted from data collected at an on-site weather station were statistically correlated with erosion data. Erosion data were collected from erosion pins installed in four gully systems at 78 locations spanning three different morphological settings: interfluves, channels, and sidewalls. Kruskal–Wallis non-parametric tests and Mann–Whitney U-tests indicated that different morphological settings within the gully system responded differently to precipitation ($p < 0.00$). For channels and sidewalls, regression models relating erosion and precipitation parameters retained antecedent precipitation and precipitation accumulation or duration ($R^2 = 0.50$, $p < 0.00$ for channels, $R^2 = 0.28$, $p < 0.00$ for sidewalls) but precipitation intensity variables were not retained in the models. For interfluves, less than 20% of variability in erosion data could be explained by precipitation parameters. Precipitation duration and accumulation (including antecedent precipitation accumulation) were more important than precipitation intensity in initiating and propagating erosion in this geomorphic and climatic setting, but other factors including mass wasting and eolian erosion are likely contributors to erosion. High correlation coefficients between aggregate precipitation parameters and erosion indicate that a suitable temporal scale to relate precipitation to soil erosion is the synoptic time-scale. This scale captures natural precipitation cycles and corresponding measurable soil erosion.

1. Introduction

Soil erosion by water is universally known as one of the main reasons for land degradation. An estimated 100,000 km^2 (10 million hectares) of cropland are lost due to soil erosion each year, a rate 10 to 40 times greater than soil development by natural processes (Pimentel, 2006). Erosion leads to a reduction in soil water absorption capacity; up to 300 mm less water per hectare per year from precipitation is absorbed in moderately eroded soils compared to non-eroded soils (Pimentel, 2006). The eroded sediment is often deposited in streams or lakes, which increases turbidity, disrupting aquatic ecosystems and contaminating drinking water supplies (O'Geen and Schwankl, 2006; Pimentel, 2000; Robertson et al., 2004). Eroded sediment that accumulates in streams and lakes takes up space that could otherwise be used to store water, and in combination with increased runoff from reduced infiltration capacity, sediment accumulation in streams can increase flood risk and flood damage potential (Kron, 2005; Plate, 2002). In the United States, 200,000 km (124,010 mi) of streams and 2851 km^2 (704,495 acres) of lakes, reservoirs, and ponds are impaired due to the presence of sediment (US Environmental Protection Agency, 2014a), including 9603 km (5967 mi) of sediment-impaired streams and 74 km^2 (18,175 acres) of sediment-impaired lakes, reservoirs, and ponds in Tennessee (US Environmental Protection Agency, 2014b).

Gully erosion, a severe type of erosion by water, when compared to sheet and rill erosion, causes considerable soil loss and soil degradation (Poesen and Govers, 1990; Steegen et al., 2000; Valentin et al., 2005). Gully erosion begins when runoff concentrates into channels and rills develop which may later enlarge into deep trenches in the land surface over time. During early stages of development, gullies grow rapidly to large dimensions (Nachtergaele and Poesen, 2002; Thomas et al., 2004; Vanwalleghem et al., 2005) inhibiting effective control by tillage, and hence reclamation can be very expensive.

Climatic factors, often in combination with other factors, play an important role in gully formation (Li et al., 2004). Frequent and abrupt changes in temperature and precipitation are signs of climate instability, which result in soil erosion (Peizhen et al., 2001; Warrick et al., 2012). A thorough understanding of gully erosion with respect to local climatic

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conditions is essential for effective planning, land management and conservation (Poesen et al., 2003). The impacts of climatic and meteorological factors on gully erosion has been widely studied (Nearing et al., 2005; Poesen et al., 2003) through modeling (Baartman et al., 2012; Favis-Mortlock and Boardman, 1995; Li et al., 2011; van Oost et al., 2000; Williams et al., 1996), laboratory experiments (Berger et al., 2010; el Kateb et al., 2013; Römkens et al., 2002), and field studies (Angel et al., 2005; Baartman et al., 2012; Capra et al., 2009; Hancock and Evans, 2010; Smith and Dragovich, 2008; Wei et al., 2010).

Simulated precipitation is used in lab experiments, which enables control over precipitation intensity and duration, but understandably cannot fully capture the wide range of natural precipitation parameters and their spatial variation at the field scale (Sirvent et al., 1997; Stroosnijder, 2005). Also, the lower impact energy of the simulated precipitation compared to that of natural precipitation is probably the primary reason for the difference in soil loss (Mathys et al., 2005). Laboratory experiments that simulate field conditions enable control of relevant physical parameters such as soil type, topography, slope, and precipitation, and are necessarily performed on plots that can be orders of magnitude smaller than typical field studies (el Kateb et al., 2013; Römkens et al., 2002). Sediment loss due to gully erosion depends on the spatial scale under consideration, and scaling up soil loss rates from lab scale to field scale can result in an order of magnitude underestimate of field scale erosion rates (Poesen et al., 2003).

Gully erosion research has been conducted also at the field scale. Hancock and Evans (2010) examined gully erosion at the hillslope scale in an Australian summer dry climate using erosion pins. Smith and Dragovich (2008) also used erosion pins to examine post fire erosion in Australia at monthly time scales. Prosser and Slade (1994) conducted flume experiments on a degraded vegetation covered valley to study the influence of climate and land use on gully formation in southeastern Australia. Also using flume experiments, Prosser et al. (1995) studied the effect of intense grazing and gully formation in humid, costal Californian natural grassland plots.

A few studies have investigated the relationship between precipitation intensity and soil erosion at the plot scale under natural precipitation conditions over several years (Baartman et al., 2012; Keay-Bright and Boardman, 2009; Porto et al., 2014; Wei et al., 2010). Capra et al. (2009) investigated the relationship between gully erosion and the precipitation erosivity factor in a cultivated catchment in Italy at a yearly scale. These studies, however, have mainly focused on erosion and runoff at the plot or regional spatial scales, or at monthly or annual time scales of measurement under semi-arid or Mediterranean precipitation regimes.

A monthly or yearly time scale may not be the ideal temporal resolution to capture the natural variation in precipitation patterns. Angel et al. (2005) studied storm erosivity for the United States on a regional basis using 15 minute precipitation data, and there is a need to link the results from precipitation studies like theirs to quantitative erosion data at the hillslope scale. Such event-based field measurements taken under natural precipitation conditions may be scarce because of the longer time commitment required for fieldwork, the length of study periods necessary for representative data, and the need to cope with natural variability in the physical systems which are beyond the control of the study (Gómez et al., 2003; Sidorchuk and Golosov, 2003; Siepel et al., 2002). Additionally, soil erosion may take place at a different temporal scale from the scale at which precipitation measurements are made. An understanding of erosion response to precipitation at an optimum temporal resolution is necessary to relate short term soil erosion response to precipitation accumulation, intensity, and duration.

A separate, but related issue is the variability in erosion between different morphological areas of a gully in response to precipitation events. Recent research in South Africa's semi-arid Karoo badlands region has shown that channel erosion in colluvium behaves in a “cut-and-fill” manner in that the measured erosion is small, but the quantity of material moved through the channel is nearly an order of magnitude greater than the measured erosion because sediment is eroded and redeposited in successive events (Keay-Bright and Boardman, 2009). Moreover, within a gully system there is significant contribution of sediment from sidewalls and interfluve/interrill areas. In Sicily's Mediterranean climate, Porto et al. (2014) estimated the soil contribution from interrill/rill erosion at the catchment scale to be of similar magnitude to the contribution from ephemeral gully erosion in cultivated silty clay loam soils. Martínez-Casasnovas et al. (2009) suggest that sidewall processes can contribute more than half of the total sediment eroded from gullies. These studies examined gully erosion under semi-arid and Mediterranean precipitation regimes, and demonstrate the need to separately examine erosion within different morphological areas of a gully system (i.e. channels, sidewalls, and interfluves).

Precipitation–erosion studies using actual precipitation records on hillslopes have been conducted in regions with very different soil and climate conditions than those present in Ultisols in the humid subtropical climate of southeastern United States (Hancock and Evans, 2010; Keay-Bright and Boardman, 2009; Sirvent et al., 1997; Smith and Dragovich, 2008). Gully erosion in the southeastern United States, particularly in the Appalachian Valley and Ridge and Piedmont provinces, given the areal extent is a greatly under-researched area. Primary causes of erosion are the wet and humid climate of the region, steep hillslopes, erodible Ultisol soil, and a transition in land cover from woodland to farmland (Trimble, 1974; Galang et al., 2007). Land cover change, linked to nineteenth century European settlement in the southern Blue Ridge Mountains, results from logging and conversion of forest lands to crop and pasture lands (Leigh and Webb, 2006; Price and Leigh, 2006; Reusser et al., 2015). Harvesting on the steep Appalachian hillslopes is identified as one potential cause of soil erosion (Kochenderfer et al., 1997) and logging activities in mid-twentieth century increased both erosion and mass wasting (Eschner and Patric, 1982; Kochenderfer et al., 1997). A long period (1820–1920) of gully erosion in the sandy loam soils of the Piedmont province is attributed to the region's cotton cultivation followed by pasture land and animal grazing (Trimble, 1974). As part of present soil conservation efforts, afforestation on the reclaimed land has partially halted the erosion, but older gullies from the past cotton farming era are still prominent (Galang et al., 2007). Previous studies using a variety of techniques have estimated the average erosion rate of the Piedmont ranging from 0.04–0.05 mm/year (Hack, 1978; Matthews, 1975) to 0.46–2.47 mm/year (Cain, 1944; Reusser et al., 2015; Staheli et al., 1974). Ireland et al. (1939) and Morgan (2005) describe a multi-stage gully development process in the Appalachian Piedmont: (i) gullies initiate along existing paths, tracks, ditches, or animal burrows, resulting in concentrated runoff due to reduced infiltration; (ii) head scarp erosion occurs from high energy, concentrated runoff in steeply sloped land; (iii) gully deepening stabilizes when the saprolite layer and the shallow groundwater zone are encountered; (iv) erosion continues along the channel sidewalls and headwalls by slumping and undercaving. According to Davis (1919), the unique climatic conditions in southeastern US are also responsible for continued gully erosion. Contrary to the northern USA climate, cold periods in the south are short and winters are too mild to cause deeper ground freezing. The thin surface layer (5–10 cm) of frost heaved soil becomes loose after a few freeze thaw cycles, and can erode easily from subsequent heavy rain or snow melt runoff. This process has been observed in the humid continental climate of northern China (Hu et al., 2007).

The problem of soil erosion in humid subtropical climates is widespread. These soil and climate conditions exist not only in southeastern USA, but also in India, southeast China, and eastern Australia. This research will therefore be of interest to soil scientists in these regions. This study uses field research and empirical modeling to investigate the relationship between natural precipitation characteristics (total accumulation, duration, and precipitation intensity) and gully dynamics in the humid subtropical climate of the southern Appalachian Valley and Ridge physiographic province.