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Gully erosion and freeze-thaw processes in clay-rich soils, northeast Tennessee, USA

Nicolas Barnes[a], Ingrid Luffman[b,*], Arpita Nandi[b]

[a] Department of Geography and Anthropology, 27 Howe-Russell-Kniffen Geoscience Complex, Louisiana State University, Baton Rouge, LA, USA 70803
[b] Department of Geosciences, East Tennessee State University, 325 Treasure Lane, Johnson City, TN, USA 37614-1709

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ABSTRACT

This study examines gully erosion in northeast Tennessee hillslopes in the Southern Appalachian Valley and Ridge physiographic province, where a thick sequence of red clay Ultisols (Acrisol, according to the World Reference Base for Soil) overlies dolomite and limestone bedrock. The role of freeze-thaw processes in gully erosion was examined weekly from 6/3/2012 to 9/17/2014 using a network of $n = 78$ erosion pins in three geomorphic areas: channels, interfluves, and sidewalls. Freeze-thaw days were identified using meteorological data collected on site. When freeze-thaw days occurred, erosion and deposition increased and gully conditions were more dynamic. When daily temperature did not plunge below freezing, more stable gully conditions persisted. Ordinary Least Square regression models of erosion pin length using freeze-thaw events explained significant portions of variability in channels ($R^2 = 0.113$, $p < 0.01$), interfluves ($R^2 = 0.141$, $p < 0.01$), and sidewalls ($R^2 = 0.263$, $p < 0.01$). Repeat analysis on only the winter-spring months minimally improved the sidewall model ($R^2 = 0.272$, $p < 0.01$). Erosion in interfluves exhibited a lagged effect, and was best correlated to freeze-thaw events during the prior period while erosion in channels and sidewalls was related to freeze-thaw events in the current week. Of the three geomorphic areas studied, sidewall erosion was best modeled by freeze-thaw events which contribute to widening of gullies through mobilization of sediment and mass wasting. This research demonstrates that freeze-thaw processes are a significant contributor to erosion in gully channels, interfluves, and especially sidewalls, and therefore temperature variability should be considered in erosion studies in similar climates.

1. Introduction

Approximately two thirds of the 3031 million hectares of potential arable land worldwide is degraded. Globally, natural erosion is estimated to total 9.9 billion tons of soil a year [1]. Erosion leads to a reduction in soil water absorption capacity; precipitation absorption is reduced by up to 300 mm per hectare per year in moderately eroded soils, reducing agricultural and plant life stability over time. In the United States, an estimated 3 billion tons of soil is eroded each year at an annual cost approaching $38 billion [2]. In the southern Appalachians, the dominant soil order, Ultisols (Acrisol, according to the World Reference Base for Soil), is highly susceptible to erosion. Worldwide, Ultisols occupy ~8.1% of the global ice-free land area, supporting 18% of the world's population, and in the USA, they occupy ~9.2% of the total land area. If left unmanaged, these soils can develop into systems of gullies characterized by deep channels and steep walls of sediment [3] that typically range from 0.5 m to as much as 25–30 m depth [4].

Gully erosion, a severe type of soil erosion, is a process whereby runoff water accumulates and often recurs in narrow V or U shaped channels with considerable depth [3]. Gully erosion starts with overland flow, which erodes small rills as flow concentrates in separate channels. Over time, rills may develop into gullies, causing significant soil loss and land degradation [3,5]. Gullies are composed of several continuous or discontinuous channels and rills with varying slopes, which may later develop into deep trenches, inhibiting effective remediation by tillage [6–9]. Gully formation and growth are governed by natural and anthropogenic factors such as: topography, soil type and texture, vegetation type and cover, precipitation amount and duration, freeze-thaw cycles, and agricultural activities [10–12]. Additionally, construction and fire are known triggers of gully erosion [13,14]. Soil degraded by gully erosion is associated with loss of soil mass, loss of nutrients, and reduction of the soil's capacity for biological activity [1]. With the loss of biological and water absorption capabilities, runoff increases allowing a greater amount of erosion to occur [10].

* Corresponding author at: Gully Erosion and Freeze-Thaw Processes in Clay-Rich Soils, Northeast Tennessee, USA.
E-mail address: luffman@etsu.edu (I. Luffman).

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The impact of climatic factors on gully erosion has been extensively studied [15, 3] through laboratory experiments [16–18], and field studies [19–23, 14]. Laboratory experiments generally mimic field erosion conditions to study the effect of important physical parameters such as soil type, topography, slope, and precipitation, performed on plots orders of magnitude smaller in scale than typical field studies [17,18]. Field scale gully erosion research has been conducted under different climatic conditions using a variety of methods, and temporal and physical scales. Using erosion pins, hillslope-scale gully erosion was studied in an Australian sub alpine environment following fire [22] and using a sediment budget approach at monthly time scales [14]. Flume experiments have been employed to examine erosion on degraded vegetated plots in Australia [24] and natural grassland plots in California [25].

While soil erosion is traditionally attributed to water and rainfall, it is also influenced by wind and freeze-thaw processes [2]. Freeze-thaw processes are ranked as the third major driver for soil erosion after fluvial and aeolian processes by Zhang et al. [26] in a study of erosion in Tibet. Freeze-thaw related soil erosion in humid subtropical climates is globally widespread in India, southeast China, and eastern Australia [27,28]. Soil freeze-thaw, a dynamic process which dramatically affects the shear strength parameters of a frost-susceptible soil, reduces soil stability on slopes. Moreover, freeze-thaw processes lower the soil's ability to resist water flow and change the depth of channels by freeze-thaw induced mudflows, slumps, and slides. Soil deposited in channels is later removed by water flow, which has the net effect of changing the shape of the rills from a rectangular to triangular cross-section, increasing the hydraulic radius [29]. In the Southeastern US, short and mild winters limit deeper ground freezing and 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 [30]. Soil freeze-thaw processes have been evaluated through a number of lab and field experiments, but are under-represented in the literature for the humid subtropical climate of the southern Appalachian Valley and Ridge physiographic province.

Several lab studies have researched the effects of freeze-thaw on soil. Ferrick and Gatto [31] examined the effect of a single freeze-thaw cycle on silt filled bins with a range of soil moisture, slopes, and flow rates, concluding that the bins subject to freeze-thaw experienced increased sediment load and rill development compared to controls. In a similar experimental setup, Edwards and Burney [32] found that freeze-thaw increased sediment loss by 90% under a rainfall simulator, which was further increased under conditions of overland flow. In addition to lab experiments on bare soil, a study using a vegetated rectangular rill subject to multiple freeze-thaw cycles showed an increase in soil water content and a reduction in soil cohesion sufficient to induce soil slumps and mud flows along the sidewalls. Further, water flow in rills occurred intermittently during thaw periods, which removed some of the accumulated soil [29]. When vegetation cover is present, erosion may be delayed after freeze-thaw events due to varied responses to freeze-thaw events among plant species [33].

At the field scale, freeze-thaw is understood to be an important driver for erosion but is generally quantified with spatially and temporally coarse precipitation and temperature data. Zhang et al. [26] classified freeze-thaw erosion in loess deposits and relatively loose colluvial, aeolian, and alluvial deposits in the dry climate of the Qinghai–Tibet Plateau using annual temperature range, annual precipitation, slope, aspect, vegetation, and soil type to develop a classification map for freeze-thaw erosion. In a separate study, Kong and Yu [34] developed a model for freeze-thaw erosion potential in a wetland dominated watershed in northeastern Tibet using annual freeze-thaw cycle days, average diurnal phase-changed water content, annual average precipitation, vegetation coverage, and aspect. The timing of freeze-thaw events followed by rainfall is also important in gully retreat by headward erosion. In northeast China, gully retreat was measured at 8.6 m per year when spring rains were followed freeze-thaw and snowmelt [28]. Zwissler et al. [35] studied soil erosion in the temperate climate of Maryland, USA, and related freezing and thawing to soil properties, freezing rate, and available water supply at a seasonal scale, concluding that depth of soil freezing and freeze-thaw cycle duration and frequency are responsible for soil erosion. Other field studies have correlated soil texture with freeze-thaw susceptibility such that coarse grained soils (gravels and sands) are least susceptible to frost action while finer textured sand, silt, and clay rich soils are most susceptible [36,37].

While the above-mentioned field studies recognize the importance of freeze-thaw in erosion, the first two studies approach the research from a modeling perspective, and the third and fourth studies examine erosion at a seasonal time scale. Quantitative field research on erosion and freeze-thaw in diverse climatic conditions and soil types is distinctly lacking in the literature, particularly at fine spatial and temporal resolutions and in the humid subtropical climate of southeastern United States, where gully erosion in Ultisols is common. Given the areal extent of gully erosion in Ultisols of the Piedmont and Appalachian Valley and Ridge provinces of the southeastern United States, the area is greatly under-researched in terms of soil erosion studies. Erosion in this region is attributed to the humid climate, steep hillslopes, erodible soil types, and a historical land use transition from woodland to farmland [38,39]. In the Piedmont, gully erosion in the province's sandy loam soils is related to the area's cotton cultivation (1820–1920) followed by pasture land and animal grazing [38]. Afforestation on the cultivated land has partly ceased erosion, but older gullies from the past cotton farming era are still prominent [39]. Previous studies have estimated the average soil erosion rate of the Piedmont ranging from 0.04–0.05 mm/year [40,41] to as high as 0.46–2.47 mm/year [42,12,43]. In the Appalachian Valley and Ridge province, initiation of gully formation is associated with land cover changes related to logging, conversion of forest lands to crop and pasture lands, and harvesting during nineteenth century European settlement [44,45,12].

Two prior projects at the study site have investigated the region's gullied soil characteristics and precipitation parameters [46,47]. In the first study, silty clay rich Ultisols derived from Ordovician to Cambrian aged, siliceous dolomite and magnesian limestone were cored from eroding and non-eroding sites. Assessment of the soil physico-chemical properties found that a silty clay texture, increased bulk density and reduced hydraulic conductivity in the Bt horizon, and soil subsurface tunneling by burrowing animals are good indicators of gully erosion in southern Appalachian Ultisols [46]. The second study examined the role of precipitation accumulation, duration, and intensity on gully erosion, concluding that different morphological settings within a gully respond differently to precipitation-driven erosion. Specifically, channel erosion is related to precipitation accumulation, while sidewall erosion is related to precipitation duration, and precipitation intensity is not a significant factor in erosion at this site [47].

The present study examines freeze-thaw erosion in a hillslope gully system at weekly time scales using a system of erosion pins and an on-site weather station. Prior research at this location that examined the role of precipitation explained up to 50% of the variability in gully erosion. The present study is a follow-up to examine the incremental role of freeze-thaw processes in facilitating erosion at this site. The objective of the study is, therefore, to quantify the relationship between freeze-thaw cycles and gully erosion in a well-established gully system at weekly time scales in an annual and seasonal context. Investigating the relationship between freeze-thaw and gully erosion in Ultisols of the Southern