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Valley floor gullies are entrenched, narrow gullies that form in sediment fills/fans found in some low order valley floors of the Southern Piedmont. Sedimentologically disconnected from uplands, valley floor gullies may in time connect with upland gullies, allowing sediment and solutes related to changing upland land uses to travel more quickly into larger streams. The development of valley floor gullies can be dated using exposure ages of gully tree roots based on anatomical changes in root ring structure. We collected tree root cores and entire root sections, as well as gully cross-section measurements from three valley floor gullies in Guilford County, NC. The root growth rings were analyzed to determine the age of root erosional exposure and the approximate timing of gully headwall migration past roots. Gully headward erosion rates were calculated to be 3.08, 0.97, and 2.03 myr^{-1} for the three valley floor gullies studied. Extrapolation of root exposure age vs. distance curves predicts corresponding ages of connection with upland gullies of 25.0, 163.0 and 49.3 years. Sediment yields based on valley floor gully volumes alone are 87.8, 27.3, and 45.8 Mg $km^{-2}yr^{-1}$ respectively for the three gullies studied. These values are greater than published estimates of background yields in forests, but less than peak sediment yields of historical agriculture reported in the literature.

EXTENSION RATES OF VALLEY-FLOOR GULLIES, CONNECTIVITY, AND THE REMOBILIZATION OF SOUTHERN PIEDMONT LEGACY SEDIMENT

by

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Approved by

Dr. Dan Royall
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APPROVAL PAGE

This thesis written by Alexis Doren has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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To my sons, Sebastian and Max, your smiles, your laughter, and your curious minds, have been my constant source of strength. Your courage, your infectious energy, and your boundless joy are my reason for living. To both of you, thank you for being my sunshine every day, for making me a better person, and for showing me what true love really is. I'm so proud of both of you.

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CHAPTER I: INTRODUCTION

Most small watersheds in the southern Piedmont experienced moderate to severe agricultural erosion after colonization by Europeans in the 17th century. This intense erosion, which lasted through at least the early 20th century, removed soils by sheetwash, rill, and gully erosion over broad areas (Trimble, 1974). Upland gullies extending from topslopes to valley bottoms are nearly ubiquitous in southern Piedmont landscapes, remaining conspicuous and often semi-active even under fully forested conditions (Ireland, et al., 1939; Trimble, 1974). Historically, a portion of eroded soil passing from and through these gullies moved into nearby streams; but most of the material was trapped and stored on valley floors downslope, forming thick fan-like deposits of sediment often overlying a visible buried A-horizon representing the pre-colonial land surface (Fig. 1). This sediment is commonly referred to as "legacy" sediment because it represents the legacy of past human land uses that accelerated erosion of upland landscapes (James, 2013; Dearman and James, 2019).

Figure 1: Buried A-Horizon

Gully bank exposure containing roughly 1 meter of high chroma variably stratified legacy sediment overlying a dark buried A-horizon (indicated by the orange hand trowel) marking the pre-colonial land surface.

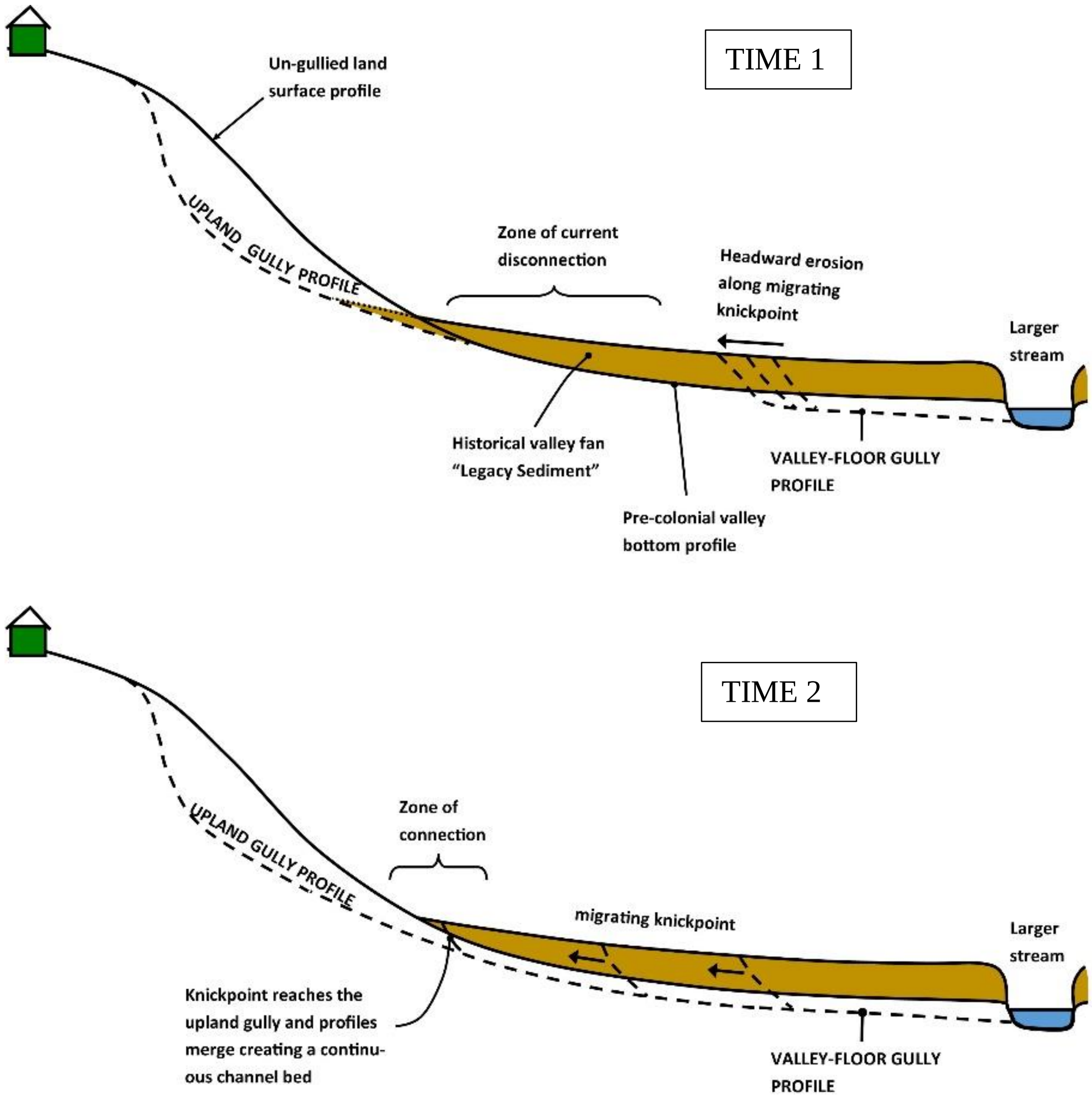
Today, new land uses in upland areas produce materials including urban runoff, sediment, and dissolved lawn fertilizers and pesticides that can likewise be stored and dissipated across and within sediment fans. However, in many Piedmont watersheds, including places like Richardson-Taylor Preserve in Guilford County, North Carolina, deep narrow gullies called *valley-floor gullies* (Ballesteros-Canovas et al., 2017), mentioned (but not well described) in parts of the southeastern US as early as 1940 by Happ et al. (1940), have developed naturally in some locations branching from larger streams and eroding their way headward into the historical valley fan sediments (Fig. 2). Similar features have been described by Campbell (1989), Faulkner (2008), and Ballesteros-Canovas et al. (2017) in relation to badland landscapes in more arid climates.

Figure 2: Photo of Valley Floor Gully in Guilford County, NC

As the heads of valley floor gullies erode upslope, they move previously stable fan sediment into streams, while getting ever closer to the bottoms of the old *upland* gullies, to which they may eventually connect (Fig. 3)(Faulkner, 2008). Upon connection, materials washed downslope from the modern uplands will be able to move more directly and quickly through upland gullies, and into the connected valley-floor gullies, emerging with little dilution or dispersion into larger streams.

This thesis project utilizes a mixture of methods including the use of root tree-ring anatomy for dating gully growth, field surveys of gully morphology, and mapping from digital elevation data to determine the rates of gully erosion, the sediment yields from that erosion, and estimates of gully connection times for three valley-floor gully networks in the southern Piedmont of Guilford County, NC. The major benefit of the study is to enable land use managers to anticipate and potentially mitigate the potential for environmental harm to small Piedmont streams here and in other similar locales throughout the southern Piedmont region.

Figure 3: Longitudinal Profile of Gully-Fan Landform Assemblage and Knickpoint Migration



Longitudinal profile of gully-fan landform assemblage, zone of disconnection and the headward erosion with a migrating knickpoint (TIME 1 image). Knickpoint migration extends the valley floor gully upslope to connect upland and valley floor gullies (TIME 2 image). The resulting continuous channel bed profile more efficiently connects upland processes to larger streams.

The knowledge gained will be helpful most specifically for Guilford County land managers with an interest in mitigating any impacts on water quality and stream ecosystems that might result from urbanization and other new land uses in upland areas adjacent to this and similar local areas. Gully extension rates measured at Richardson Taylor Preserve, a location exhibiting many characteristics in common with all Piedmont watersheds, may offer hypothetical estimates for the southern Piedmont more generally.

Hypothesis 1

Valley floor gullies are young features with likely initiation ages post-dating secondary forest growth beginning 50-80 years ago in this area and are ultimately capable of connecting to upland gullies in a matter of decades rather than centuries.

Hypothesis 2

Valley floor gully erosion rates will obey the Rate Law (Graf 1979), demonstrating a reduction in headward extension rates through time as network extension reduces drainage area.

CHAPTER II: BACKGROUND

The term *legacy sediment* has been defined by James (2013) as “sedimentary deposits generated episodically by human activities.” Although the term can now be applied more broadly, it originally derives from descriptions of sediments in the eastern U.S. that were produced by highly erosive activities, particularly upland agriculture, during post-colonial time (between approximately CE 1700 and 1920) (Royall, 2020). The generalized history of anthropogenic erosion and sedimentation are well documented for the southern Piedmont (Ireland, 1938; Wolman, 1967; Trimble, 1974, 1985). Yet, detailed case studies continue to provide important new insights into both the history of erosion, and its environmental effects on water and soil quality (Walter and Merritts, 2008, and Spell and Johnson, 2019). Most studies have focused on the causes and rates of past erosion. The remobilization of stored legacy sediment, the product of this accelerated erosion which is known to have maintained elevated sediment loads in water bodies since the early 20th century, has received less attention, particularly regarding specific mechanisms and rates.

Campbell (1989) views badly eroded Piedmont landscapes as analogous to the “badlands” of drier climates on shales. This emphasizes that badland landforms can be more strongly related to rock types than climate. In drylands, badlands form on highly erodible shales; in the Piedmont, badland landforms formed on deep saprolite (Campbell, 1989). Faulkner (2008) describes how gully networks act like small drainage basins that may have shifting drainage divides in upland gullies and create discontinuous valley floor gullies. Discontinuity in gullies can occur and gully fragments can sometimes be created independently and then join up into a single gully (Faulkner, 2008 and Ballesteros-Canovas et al., 2017). The idea that badland landforms are likely more related to rock types than climate is a potential area for further research.

Study sites in Richardson Taylor (RT) Preserve contain classic upland gullies and legacy sediment bodies including sediment fans and tributary valley sediment fills, resulting from highly erosive Euroamerican upland agriculture. Reconnaissance of the area reveals that mobilization of legacy sediment in many locations may be dominated by valley-floor gullying processes enhanced by seepage (subsurface) erosion. Valley floor gullies show signs of rapid up-valley extension, especially deeply entrenched and incised creek/gully beds sometimes even deeper than they are wide (Fig. 4). The ages and rates of growth of these gullies, as well as the amounts of sediment yield represented by their growth, can be determined using root exposure ages (from root tree rings) for gully spanning roots (Dick et al., 2014; Stott et al., 2014; Hupp et al., 2016; Bernatek-Jakiel and Wronska Wallach, 2018).

Figure 4: Living Tree Roots Across a Deep Gully

Arrow shows the lip of the gully headwall. Living roots spanning a valley floor gully (1 – 1.2 m deep). These deeply incised gully reaches are approximately 1 meter wide (sometimes narrower). Thus a 1-meter length of gully represents the removal of up to 1.5 cubic meters of sediment.

Headward extension of valley floor gullies is important because it can over time reestablish direct sedimentological connections between uplands and bottomlands (Faulkner, 2008); in this case, between upland gullies (and currently evolving land uses around them) and distal bottomlands (main branch floodplains and receiving waters) that were sundered during the forest regrowth period beginning in the 1940s. As valley floor gullies erode their way headwards, they undermine and unearth large numbers of tree roots that then either protrude from gully banks or fully cross them from one bank and into the opposite bank due to very rapid incision or tunnel roof collapse beneath them. Once exposed, the annual wood increment in a root changes from being highly porous and soft, to less porous with smaller tracheids and vessels, and thinner increment similar to that observed in stem tree rings. This observable change is the basis for determining root exposure (and thus gully erosion) ages (Studhalter et al., 1963).

Previous studies have described challenges with using tree roots. For example, it has been noted in one paper that root ring changes can begin to occur before complete root exposure (Stotts et al., 2014). It is possible that when burial declines below 3 inches, some species' roots begin to experience early effects (Bernatek-Jakiel et al., 2020). This can make the root ring transitions more gradual and thus harder to identify an exact year. Additionally, most of the studies using root rings in gullies come from dryer climates where coniferous species dominate; and that rings from such species are often easier to identify and count which is another source of uncertainty.

Figure 5: Tree Rings in Root Samples

Root rings samples 3F1 and 3F2, showing clear reductions in vessel size which often occurs in association with a coloration change in samples; both can be seen in these samples. The color change is not uniform all the way around, probably because the root itself may not have been completely unburied on all sides at the same time. Age of exposure is approximately 6-7 years in each root.

CHAPTER III: SITE DESCRIPTION AND METHODS

The Richardson-Taylor Preserve ("RT-Preserve") is a forested passive park in Guilford County, in the north-central North Carolina Piedmont (Fig. 5). This area exhibits many of the classic features of 19-20th-century Piedmont agricultural impacts as outlined by Trimble (1974) including large gully networks, sediment fans derived from gully and other upland erosion, and wide flat floodplain/wetland areas (Fig. 6). Unlike in the Trimble (1974) model, current wide floodplain/wetland areas at RT-Preserve are mostly-to-partially inundated as a consequence of elevated water levels from Lake Townsend (downstream), and/or local beaver activity, which conspire to maintain wet conditions. The Preserve is fully forested, with upland vegetation consisting of a variety of hardwood trees, often with pine forests capping ridge crests.

Figure 6: Location of Richardson Taylor Preserve, Guilford County, NC

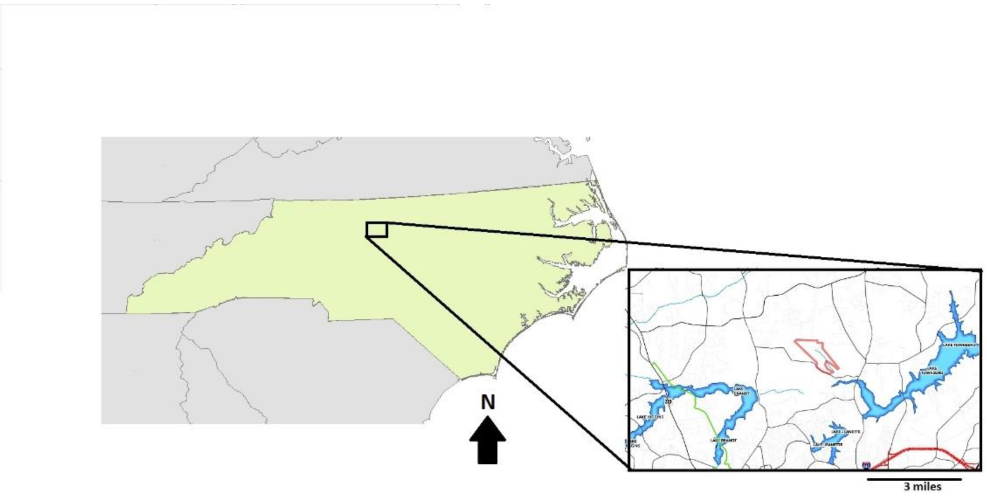
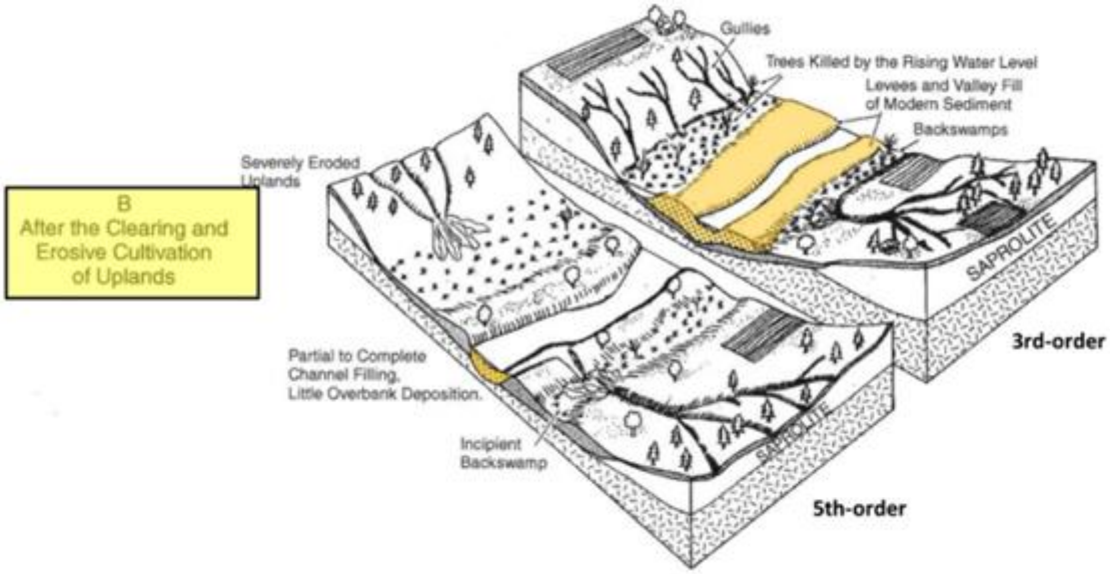


Figure 7: Trimble's (1974) Conceptual Model of Landscape Change



A conceptual model of landscape change along 3rd and 5th -order streams in the southern Piedmont (from Trimble, 1974). In this image, tan-colored sediment is of agricultural origin. Erosive land use in the southern Piedmont was generally greatest in the mid- 19th through early 20th centuries; however, local variations, sometimes extreme, may exist.

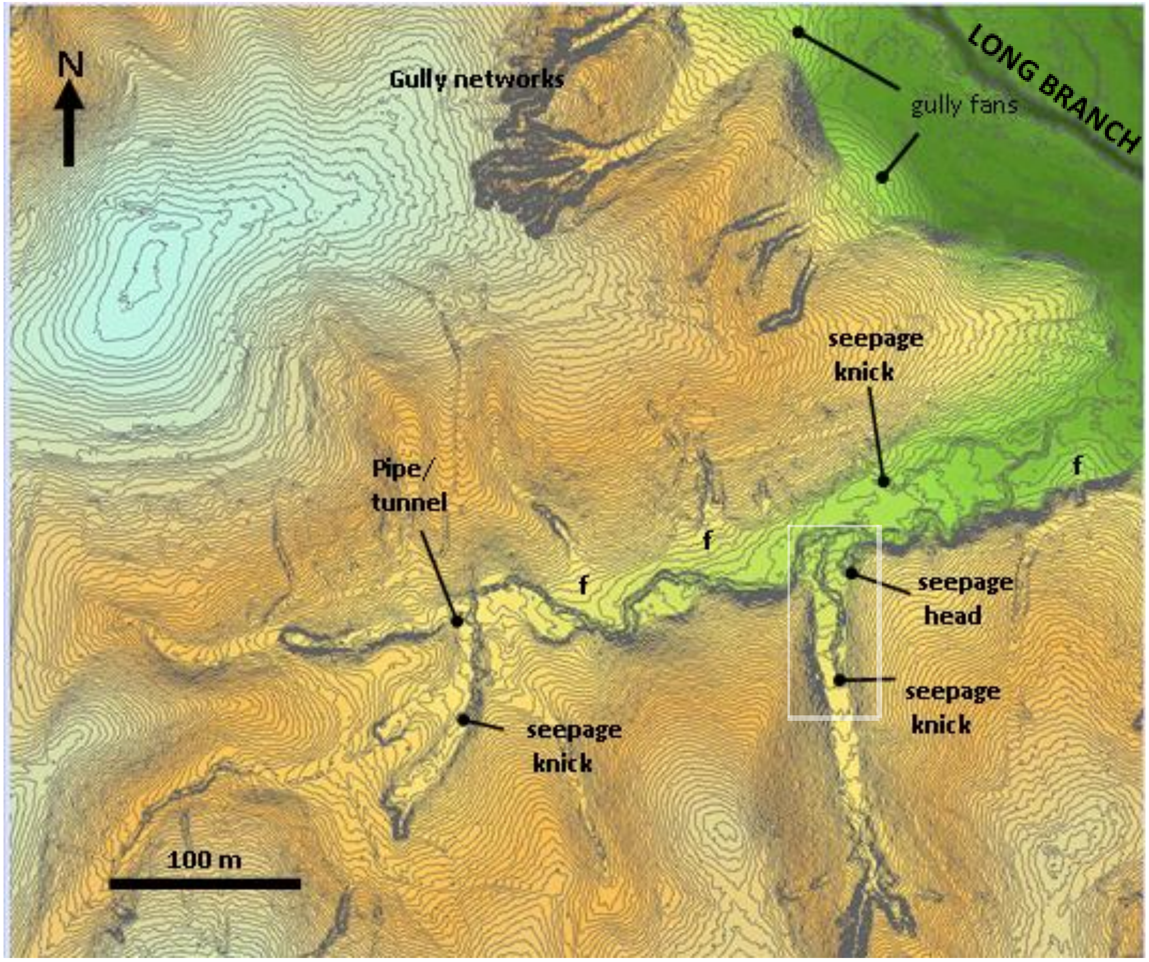
Based on tree rings in storm-felled trees (exposed in stumps presumably sawn by the County during trail clearance), upland forests were establishing no later than the 1940s, and some apparently older trees may be found in footslope areas where agriculture may have been phased out earlier in preference for more accessible, less sloping ridgecrest sites. Margins of the Preserve vary in their degree of urban/suburban development, with residential areas rapidly expanding in recent decades. Annual rainfall is roughly 100 cm. Upland soils consist largely of Poplar Forest soil series which are classified as Typic Kanhapludults, with some local Poplar Forest Udorthents in gullied areas and young fan surfaces. Bottomland soils are dominated by Fluvaquentic Dystrudepts of the Codorus loam series (NRCS; Web Soil Survey; accessed October 2022).

Two types of gullies are found in RT Preserve: upland gullies and valley-floor gullies (see Appendix 1 for definitions). Revegetated upland gullies are found almost everywhere within the Preserve, and many still contain steep unvegetated banks near their angles of repose. These gullies originated during an earlier agricultural land use phase in the uplands between approximately CE 1700 and 1930, which produced large amounts of largely uncontrolled runoff. Although these gullies are no longer nearly as active as during the agricultural phase, rainsplash erosion and shallow mass wasting remain in evidence on their banks, with the derived sediment moving towards the gully axes where it may be remobilized during large rainfall events. The rates of these modern processes have not been quantified, although it is likely that they are much lower than those under the prior agricultural land use phase.

Valley floor gullies are smaller but very steeply walled (often nearly vertical) trenchlike gullies incised into alluvial and colluvial fan sediments underlying valley bottoms. Field observations show such sediment bodies, the same as or similar to the Codorus loam are common in small valleys and are inclusions sometimes too small to be portrayed on USDA soil maps. Dry bulk density of Codorus loam is 1.11 $\mathrm{Mgm^{-3}}$ (Web Soil Survey soil data; accessed June 2022). The upper portions of valley floor sediment profiles are frequently composed largely of regolith eroded from upland gullies and thus of anthropogenic origin; this marks them as “legacy” sediments. Some valley floor gullies show evidence of rapid incision and headward extension towards upland gullies to which they are currently relatively disconnected. Evidence for rapid extension and incision includes very low aspect ratios (the ratios of gully width to gully depth) implicating some deep seepage erosion activity and lack of lateral shift, near vertical gully banks, and the frequent presence of gully-spanning living roots from nearby trees. Continued extension of valley floor gully heads by processes of surface and subsurface (seepage) erosion could eventually reconnect upland and valley floor gullies, making streams in the watershed more sensitive to changes in upland land uses bordering the Preserve (Fig. 3).

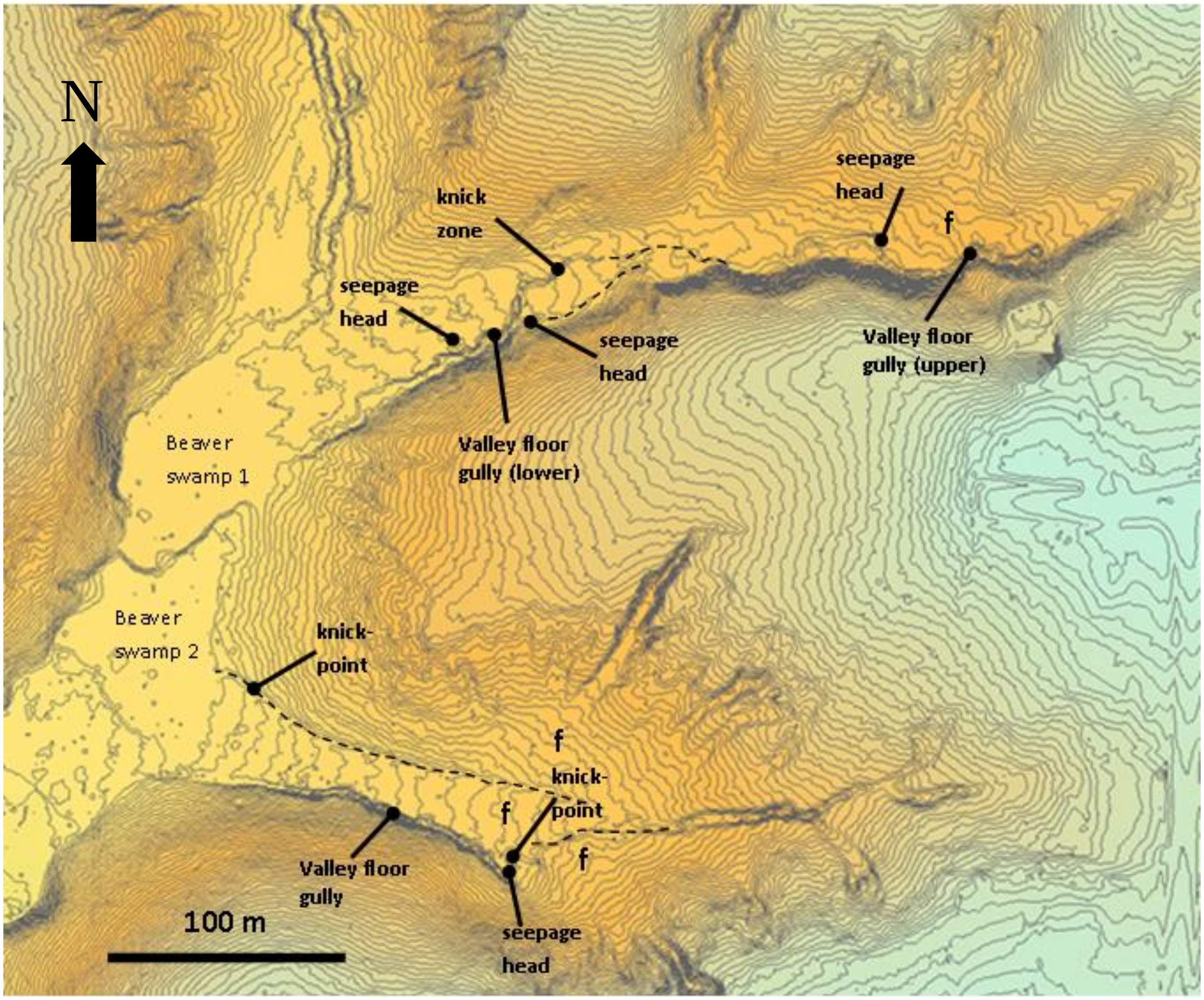
The project design was accomplished using GIS-enabled surveys of valley floor gullies, fields surveys of the dimensions of these gullies, age-dating the progress of gully extension using tree-root exposure ages determined from root tree-rings, and other basic observations of water flow and erosion mechanisms at gully heads and along gully walls. High resolution (1-m) digital elevation models, created by the state of NC in 2019 using LiDAR data collected in 2017 (NC Floodplain Mapping Program, 2016), processed with ArcGIS and TerraSet Idrisi (Figs. 7&8), and field reconnaissance were used to identify locations of prominent gully-fan assemblages exhibiting valley-floor gullies with migrating headcuts. Three study sites were selected (Sites 1, 2, and 3) with drainage areas of 0.05, 0.12, and 0.09 km^2 respectively (Figs. 7 and 8).

Figure 8: Prominent Landforms and Data Collection Site 1



Richardson-Taylor Preserve tributary valley field site 1 (white rectangle) (“f” abbreviation for “sediment fan”); see appendix 1 for landform definitions. Contour interval is 0.3048 meters (1 foot).

Figure 9: Prominent Landforms and Data Collection Sites 2 and 3



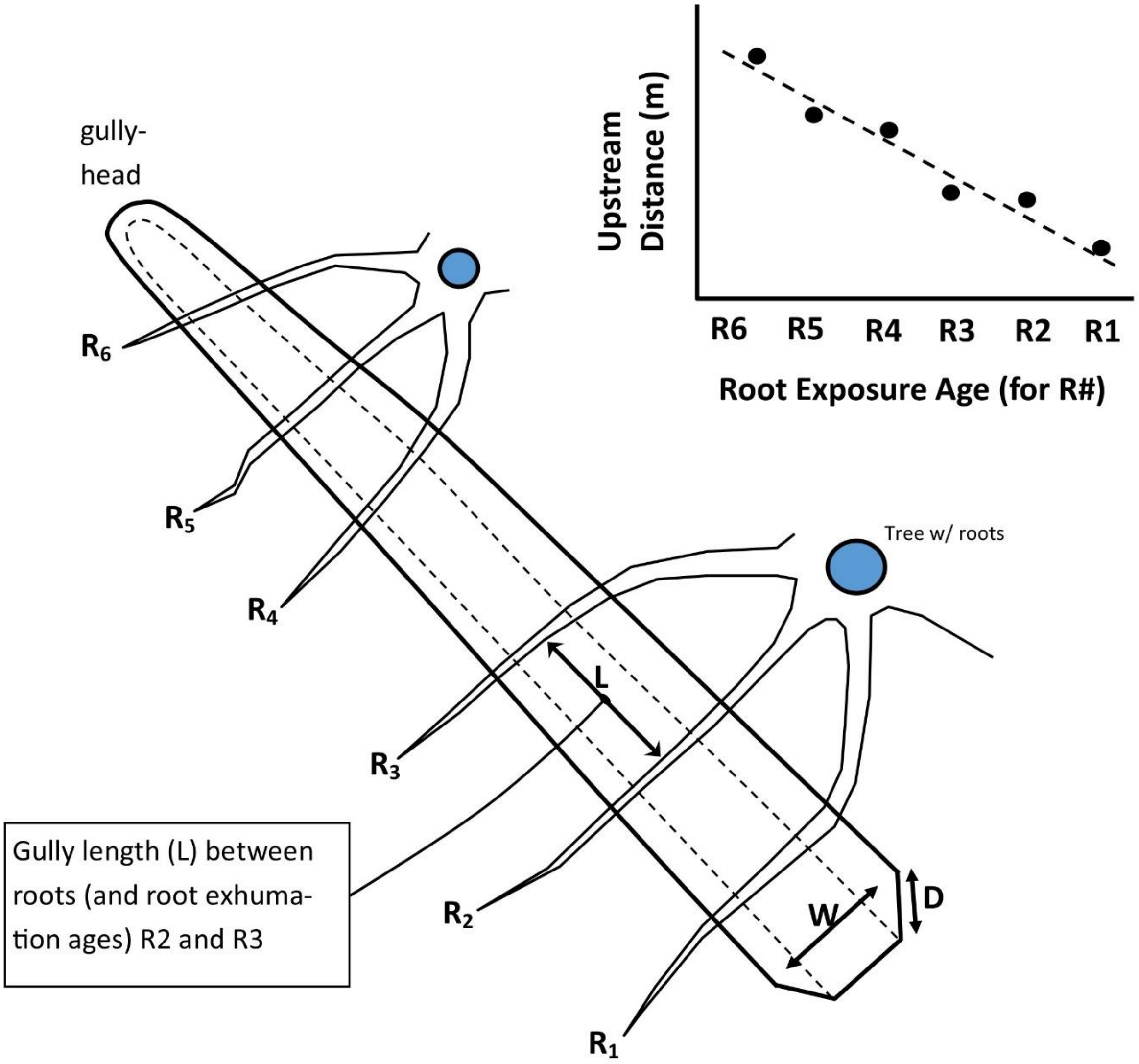
Contoured digital elevation model of northern Richardson Taylor Preserve, showing prominent landforms of the Piedmont watershed landscape, with study site 2 (uppermost valley) and site 3 (lowermost valley). These include upland gullies, sediment fans ("f" symbols), valley-floor gullies with migrating headcuts (knickpoints and knickzones), and the zones of relative disconnection between upland and valley-floor gullies. Contour interval is 0.3048 meters (1 foot)

Trans-gully and other mid-channel root exposures observed along valley-floor gullies (Figs. 4&9) were used to obtain root tree-ring samples at approximately 10 locations per site distributed along gullies.

Figure 10: Root Exposure Sampling Area

The number of new tree rings produced since root erosional exposure give an age estimate for the time at which the migrating gully headcut reached that point along the gully. Endpoints of the root sample distances were established using GPS, and distances between individual root samples were measured using a meter tape drawn along the gully axis (GPS coordinates were also collected for each root sample location, but given the short distances between a combined plot, their accuracy was insufficient for purposes other than confirmation of general location). The distance between dated root exposures, divided by the difference in exposure ages gives the headcut migration rate for each adjacent root sample interval (Fig. 10). Trends in migration rates were used to estimate the future dates of connection between upland and valley-floor gullies.

Figure 11: Gully Erosion Model

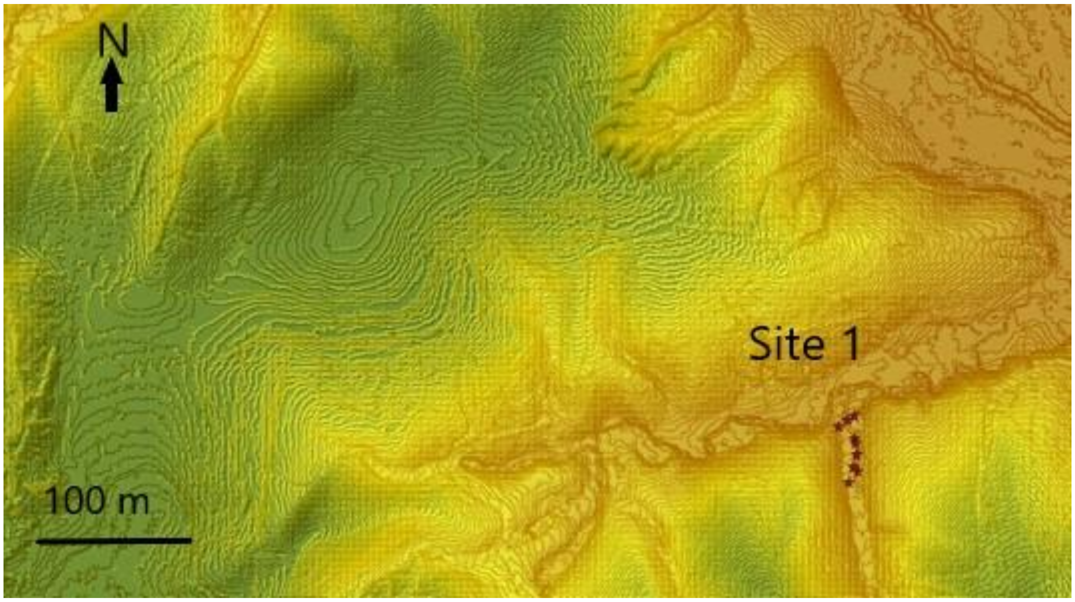


Example with six root exhumation ages (R1-R6), giving five sequential erosion rates, each corresponding to a gully length segment (L): L1,2, L2,3, L3,4, L4,5, L5,6. The volume for each length segment is WDL; converted to mass using sediment bulk density information. Erosion rate for each segment is mass divided by age difference between the bounding root exposure ages. Inset graph show hypothetical decline in headcut migration rate through time.

Root Sampling for Exposure Ages

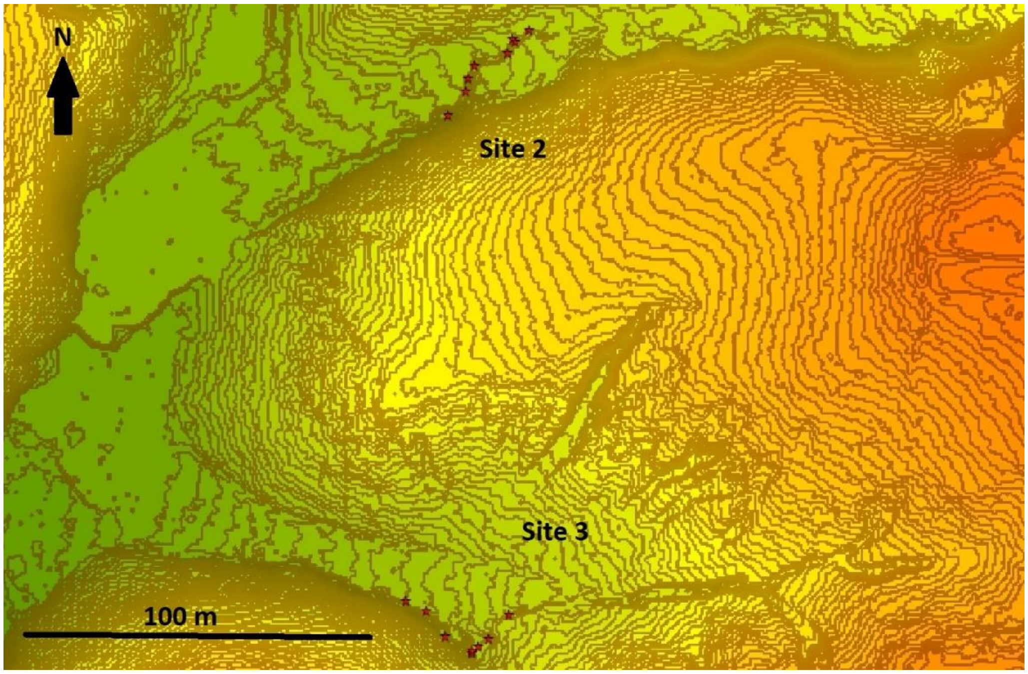
Root cores were obtained at regular intervals along a growing gully using a standard increment corer like those used for stem wood tree ring studies. Approximately 10 samples from each site were obtained (Figs. 11&12). The increment corer was used to extract a 3/16 inch diameter wood core from the root, with a length that is at least one-half the diameter of the root (usually between 3 and 10 cm in length). Some studies have used the entire cross-section of the root due to additional information about exposure direction that can be obtained from this. However, using cores instead keeps the root healthy and is in keeping with our minimally invasive approach. When necessary, an entire root sample was obtained. Although root age from ring counts alone can provide useful information on gully erosion (Vandekerckhove et al., 2001), many tree roots also display visible changes in ring structure, particularly reductions in root vessel size and better contrasts in late and early wood within rings following exposure by erosion (Bodoque et al., 2011; Stoffel et al., 2013; Dick et al., 2014). The root cores were dried, mounted on wooden mounts marked with orientation and location data, and sanded with a progression of sandpaper grits from 100 to 600 grit for microscopic examination and ring counting. First, we identified the transition ring at which vessel size and other ring characteristics change. If a good identification could not be made, the sample was not used. This may occur as a result of recent destruction of a soil bridge, or generally poor ring identification in some tree species. We obtained multiple independent ring counts to determine the number of rings added after the transition ring. If there were variations in the number over multiple counts, this was given as a range, and the midpoint was adopted as the most likely age of exposure. For the few locations at which more than one root was sampled, we accepted the larger of the ring counts for plotting purposes due to the possibility of localized soil bridging which can keep a root surrounded by soil for several years after a gully has eroded a large tunnel out from under the roots and progressed further up valley.

Figure 12: Root sample locations at Site 1



Contour interval 0.0348 meter (1 foot)

Figure 13: Root sample locations at Sites 2&3



Contour interval 0.0348 meter (1 foot)

Sediment Yield

The volumes of sediment that have been removed by valley floor gully erosion were measured using a meter tape to quantify the width, depth, and length of gullies between dated root exposures. The gullies were measured in sections between the root sample collection sites. The measurements were then used to determine the sediment volumes lost between sampled roots. Most published values for watershed sediment yield express it as the mass of sediment exported from a stream per unit watershed area per year. In this study, the translation of gully volume to mass was done by multiplying volume times the bulk density of sediment: the dry sediment mass per unit volume of sediment. Bulk density estimates for Richardson Taylor soils were obtained from the Web Soil Survey Database (NRCS, 2017); this resource gives bulk density and volumetric soil moisture at 0.3 bar water content, from which the dry bulk density of

1.11 Mg/m3 for the Codorus loam was derived and used to convert volume to mass. Gully sediment mass was divided by the drainage area delineated for each gully watershed from topographic maps, and the result divided by the duration of gully erosion indicated by root ring exposure ages to obtain a sediment yield in Mg km^{-2} yr^{-1}. Sediment yield values were calculated for each site using the gully volume and root-ring data and compared to estimated long-term background rates, and the limited available data on small stream sediment yields in formerly agricultural landscapes in North Carolina and other southern Piedmont streams.

CHAPTER IV: RESULTS

The root growth rings were analyzed to determine the age of root erosional exposure and the approximate timing of gully headwall migration past roots. A total of 28 root core and root samples were collected. Eleven samples were collected from site 1; ten from site 2: seven from the main gully and three from a side gully; and seven from site 3 (Table 1).

Table 1: Raw Data Collected

site #	Sample	Distance (m)	Age Range (years)	Age Used	Gully Cross-sectional Area (m^2)
1	1A1	28.5		16	1.7639
1	1A2	28.5	18-19	18.5	1.7639
1	1B	34	12-13	12.5	2.0805
1	O1	30.48	19-20	19.5	2.0139
1	O2	41.65		12	1.82025
1	1C	47.5		9	1.573
1	1D	54.5		10	1.28505
1	1E	63.1	3-4	3.5	2.05355
1	1F	67.3	6-7	6.5	1.7654
1	1G	74.4		6	1.8126
1	1H	81.9		2	1.3521
2	2A2	1		36	3.5193
2	2B1	13.05		26	1.35895
2	2B3	16.3	22-24	23	1.35895
2	2C1	20.2	14-17	15	1.1183
2	2D1	23.7		18	1.52235
2	2D2	24.7	11-12	11.5	1.52235
2	2E	31.8		6	1.31445
3	3B	9.7		20	2.6202
3	3C	22.6		13	2.2169
3	3D	35		6	0.47595
3	3F1	39.8	5-8	6.5	1.5318
3	3F2	40.3	6-7	6.5	0.5667
3	3Fsup	41.8		3	1.3545
3	3G2	46.6		2	2.2169

Age range in table is due to some of the samples being more difficult to read. When a consensus could not be reached, we used the average.

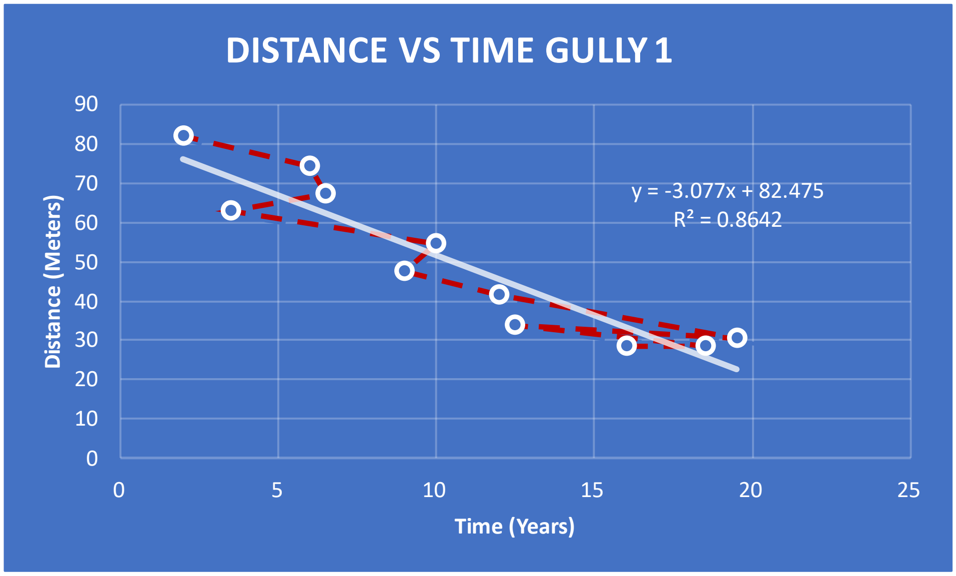
Possible Sources of Error.

Getting an accurate ring count was extremely difficult in some cases. The tree species was the biggest factor since some species of tree do not have clear rings in their roots, but we took samples of every root available for the study, so there was no choice in the species availability. Additionally, the type of tree used could also be a source of scatter since it is possible that each tree responds to a disturbance differently. There is also the possibility that in some instances, root bridges were maintained for a while even after the gully headcut had passed. Root bridges are soil bridges that have roots within them, or root supported soil bridges, which are uncollapsed portions of tunnels eroded out by subsurface flows (Fig. 16). These bridges have the effect of making the transition to full exposure (and thus presumably onset of changes in rings) less abrupt and clear. They may also delay the onset of changes in rings making the gully look much younger than it might be.

Figure 14: Example of a Root Bridge

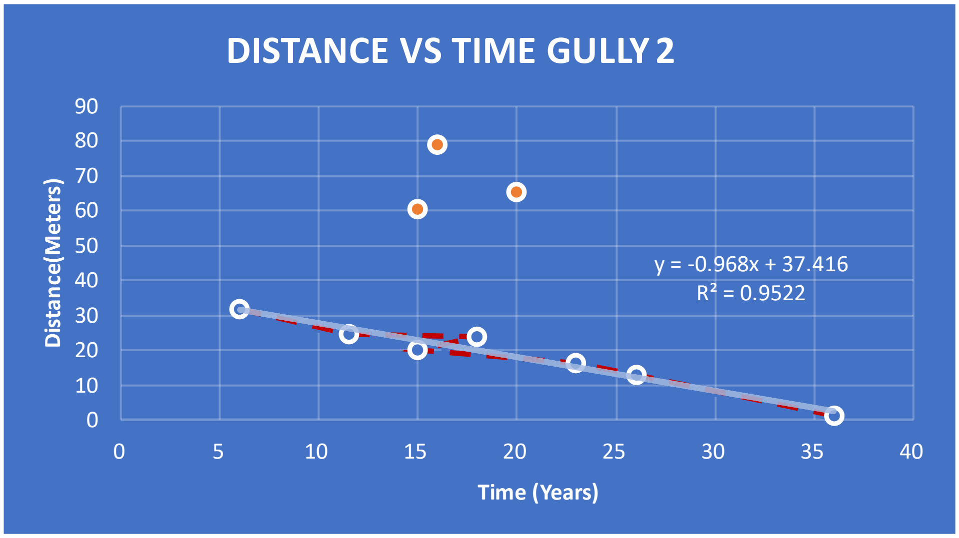
The age of each tree root was determined and then the gully distance vs. root exposure age was graphed in Excel to extrapolate the gully headward erosion rates (Figs. 13, 14, and 15).

Figure 15: Distance vs Time Gully 1



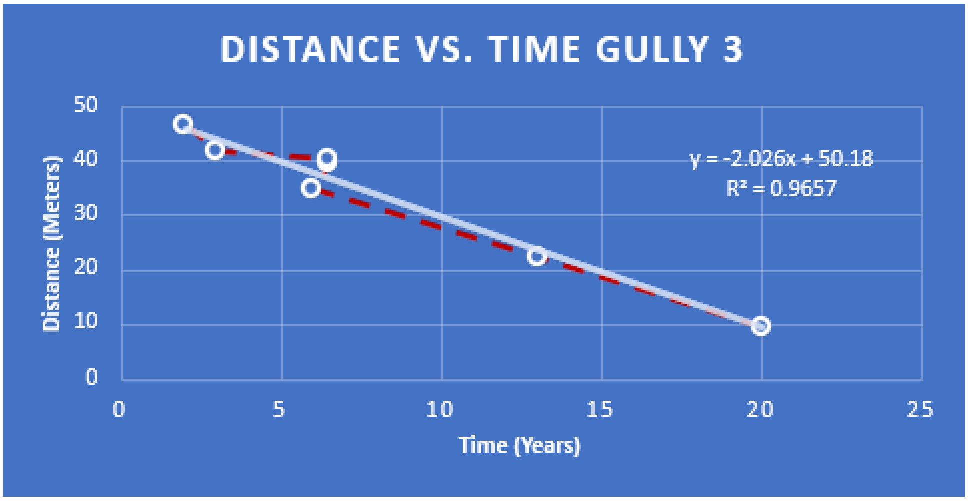
The regression line (white) was plotted to enable extrapolation of gully headwall recession rates into the future. Red dashed line shows the sequence of upstream distances; that is, the distance order of the plotting points.

Figure 16: Distance vs Time Gully 2



Data collection site #2 with regression line in white. Three orange points are root samples collected from an area farther upstream on the principal gully, within the knickzone of this gully. Red dashed line shows the sequence of upstream distances; that is, the distance order of the plotting points.

Figure 17: Distance vs Time Gully 3



Data collection site 3 with regression line in white. Red dashed line shows the sequence of upstream distances; that is, the distance order of the plotting points. Soil bridging, unknown partial exposures above or below ground, and counting uncertainties, plus the potential for gullies to form discontinuously at first before merging may create nonlinearities in the plots.

Regression lines were plotted to enable extrapolation of gully headwall recession rates into the future. The general trends of the resulting plots were arithmetic linear, and best fit by a linear equation. Gully headward erosion rates correspond to the slopes of regression lines: 3.08, 0.97, and 2.03 myr^{-1} respectively for sites 1, 2, and 3. The R^2 values for each of the gully sites was extremely high, 0.86, 0.95 and 0.97 which indicates a strong correlation between the age of the tree root exposures and gully headwall migration. The best fit trendlines are straight, and thus do not show evidence of slowing down over time as drainage area is closed out. The straight line distance from the current gully head to the upland gully is 77.1, 158.1, and 100.0 meters, respectively for sites 1, 2, and 3. Extrapolation of root exposure age vs. distance curves (using the regression equation slopes) predicts corresponding ages of connection with upland gullies of 25.0, 163.0 and 49.3 years, respectively for sites 1, 2 and 3. This is based on the current distances measured off DEMs from valley floor gully headwalls to the bases of the upland gullies farther up-valley near the drainage divide. The results are summarized in Table 2.

Table 2: Time, Sinuosity, and Distance for Each Site

Site	Erosion Rate (m/y)	Straight Line Distance to Upland Gullies (m)	Connection Time (years)	Sinuosity	Sinuosity Distance (m)	Conn. Time w/ Sinuosity (Years)
1	3.08	77.1	25.0	1.26	97.1	31.5
2	0.97	158.1	163.0	1.08	170.7	176.1
3	2.03	100	49.3	1.20	120.0	59.1

The sediment yields based on valley floor gully volumes alone are 87.8, 27.3, and 45.8 Mg km^{-2}yr^{-1} respectively for the three gullies studied (Table 3). Royall and Kennedy (2016; Table 3) cite a number of sources to derive an estimate of long-term forested erosion and sediment yield rates in the Piedmont of ~ 11-14 Mgkm^{-2} y^{-1}. The same table suggests published values for peak agricultural erosion and sediment yield in the southern Piedmont from large (>1000 km^2) drainage basins as 56-72 Mgkm^{-2} y^{-1}. For smaller basin, these values would be higher; Gregory (2006) after Wolman (1967) gives sediment yields up to 200 Mg km^{-2} y^{-1} in some Piedmont watersheds. Reusser et al (2015) state that erosion rates were generally 1-2 orders of magnitude greater during peak agriculture than in prior periods.

Table 3: Sediment Yields

Site #	Mg km^{-2}	Mg km^{-2}yr^{-1}
Site 1	1625.4	87.8
Site 2	984.4	27.3
Site 3	915.3	45.8

The rates of total sediment mobilization and export from valley-floor gullies alone are larger than the long-term background forested erosion rates for small Piedmont watersheds (less than ~11-14 Mg km^{-2} y^{-1}; cited from original sources in Royall and Kennedy, 2016; Table 3), suggesting an anthropogenically augmented erosion and/or sediment delivery system is currently operative despite reforestation more than 50-80 years ago.

The DEMs were then used to measure the distances downstream along the gully from the lowermost oldest sampled ring to the beaver swamp (the mouth of the gully). This distance divided by the slope of the regression line (the erosion rate) gives an estimate of the time it might have taken for the gully to erode up to the first sampled root. This information determines a gully initiation date, summarized in Table 4.

Table 4: Table of Erosion Rates and Times to Mouth of Gullies

Site	Drainage Area (km^2)	Distance to Mouth (m)	Gully Headcut Migration Rate (myr^{-1})	Gully Origination Age /Year
Site 1	0.05	81.9	3.08	26.7 years/1996
Site 2	0.12	138.9	0.97	143.2 years/1879
Site 3	0.09	167.2	2.03	82.4 years/1939

Counting backwards gives the years of initiation: 1996, 1879, and 1939 for sites 1,2,3 respectively. The very recent date for Site 1 could be related to the fact that it is a tributary to what once was a fan surface with a larger gully (now a small perennial stream channel). Extrapolating the erosion rate downvalley to the larger tributary and all the way to the Long Branch floodplain (about 284 m) gives an origination age of 92 years (~ 1930). Although producing an age very similar to that of site 3, the uncertainty of erosion rates on the larger tributary fan surface makes the result questionable. Site 2 showed a much higher origination date, as well as a higher connection date to the upland gully. This could be attributed to the slope of the valley which, at 0.09, was lower than the other two sites, at 0.15 and 0.16, respectively for sites 1&3. Since site 2 is near site 3, the rock and soil type probably had less to do with the difference.

CHAPTER V: DISCUSSION

In this study, the rate of headward erosion in all three gullies was linear, however it is possible that the rate of headward erosion might change as drainage area is slowly reduced. Currently the assumption in the results is no change, which is what the data show (arithmetically linear curves). However, it is possible that the straight-line plots are just a small linear portion of a rate law curve. The Rate Law is most commonly used for describing radioactive decay; however, it is also useful in geomorphology to describe changes in gully length through time (Graf, 1977). The Rate Law equation is given as

$$A_x = A_0 - A_0 e^{-bt}$$

Where t = time, A_x = the length of the gully, A_0 = the potential equilibrium length of the gully, and b is the rate constant. With the passage of each half-life, half of the length of the gully is eroded. Graf (1977) addresses a similar issue in his paper on the Rate Law in which he gives as an example how gully networks in Colorado that he dates using tree ages slow down in their erosional extension through time. In this scenario where there were reductions in upstream drainage area as gullies eroded headward, the rate of gully headwall erosion might not be linear. For the sites studied here, more data might be needed for such a determination, and this is an area where there could be additional research. Additionally, this may be a reasonable model in general, but is not an ideal application for these sites where there are upland gullies, valley-floor gullies, and some discontinuities in headcuts between them in at least one case. In these gullies there could be sudden jumps in gully extension as the lower gully connects to a gully fragment in the mid-basin area. Under such conditions, the extension rate would likely not be linear, nor even obey a rate law. Additionally, if the thickness of sediment that a gully must cut through for headward extension to take place decreases upslope (i.e., the gully being cut can be shallower and smaller), and if the rate of sediment depth decrease matches the erosional ability afforded the system by virtue of drainage area, then rates of headward extension would not change through time.

The surface channel lead-ins above knickpoints are not very sinuous, but some existing gully segments do show curvature. This sinuosity might have developed for several reasons. The type of soil could play a role in sinuosity since some soil types are more resistant to erosion. In a case where there were different soil types on each side of the gully, or more organic matter, or a higher distribution of rocks in the soil, this could affect the critical shear stress of the bank and cause sinuosity by differential bank erosion. Additionally, the type of trees in the area and where they put their roots could affect sinuosity of surface waters which might be translated to gullies either directly or by affecting changes in local groundwater tables in valley sediment that alter the direction of tunnel excavation, as well as changing groundwater flows. At this point it is not known whether the sinuosity is likely to continue as the gullies erode their way headward. Assuming sinuosity stays the same over time clearly lengthens the time to connection since a straight gully is shorter than a meandering gully. So, this could be dealt with by positing 2 scenarios: the first is already part of the analysis (straight line path); the second uses the sinuosity value of existing gullies to convert the straight-line distance into a more likely distance. The sinuosity, which is the measure of how curved the gully is in relation to the valley floor, is determined by measuring the length along the gully divided by the straight-line distance along the river valley. The result of the second scenario is summarized in Table 2.

Differences in Erosion and Sediment Yield Rates

All three gullies show vastly different headcut migration rates 3.08 m/yr; 0.97 m/yr; and 2.03 m/yr. The differences could be due to the drainage area above the gully head, although the lowest headwall retreat rate occurs for the largest drainage area (Table 4) which is counterintuitive. It could also be due to the slope of the fan surface for each gully, as well as the soil type surrounding each gully. The slope of each fan surface was determined by measuring the highest and lowest elevations of the fan surface and dividing by the straight-line distance of the valley along the gully. The results are summarized in Table 4. The table shows that the gully with the largest erosion rate has the largest slope, and the smallest erosion rate has the smallest slope. A possible explanation for this correlation might be that the slope of the fan surface might be partially determined by the headcut migration rate. In other words, a faster erosion rate could be causing a steeper slope.

Table 5: Slope of the Gullies and Headwall Migration Rates

Site	Length (m)	Elvtn high (m)	Elvtn low (m)	Fan Slope	Gully Headccut Migration Rate (m/yr)
1	81.90	762	749	0.16	3.08
2	79.00	791	784	0.09	0.97
3	68.00	789	779	0.15	2.03

However, the fan slopes at sites 1 and 3 are nearly identical, yet their headcut migration rates are distinctly different. There is another possible explanation: the combination of slope and valley width. Site 1, with the highest headwall migration rate, also has by far the narrowest valley. That means all water collected in the basin is funneled through a narrower body of sediment; Thus, the likelihood of it finding a common discharge point at which to erode a gully is higher**.** In the case, there is more water per unit valley width moving through the valley and this would increase erosion rates. Of these possible explanations, (drainage area, slope, valley width) it is likely that they all exercise some control over gully erosion and headwall migration rate. That is, they are influences, all of which operate, and the research design does not address a determination of which is most important.

CHAPTER VI: CONCLUSION

There are several important findings from this analysis. First, the gully erosion rates can be determined by tree root exposure ages. All three of the sites sampled showed a consistent arithmetic linear headward erosion rate. Hypothesis 1, which states that valley floor gullies are ultimately capable of connecting to upland gullies in a matter of decades rather than centuries, was shown to be true for sites 1 and 3, at 25.0 and 49.3 years, respectively. Site 2 this was not shown to be true, with a connection time of 163.0 years. Using the erosion rates and following the distance back to the mouth of the gully provided an estimated age of origination of the gullies. These dates were 26.7, 143.2, and 82.4 years ago, respectively for sites 1, 2, and 3. Counting backwards, the years of initiation are 1996, 1879, and 1939, respectively for the three sites. The second part of Hypothesis 1, that valley floor gullies are young features with likely initiation ages post-dating secondary forest growth beginning 50-80 years ago in this area was shown to be true for site 1. Site 3 shows an origination date of 82.4 years ago, which is close to the upper end of the secondary forest growth. Since the secondary forest growth is an approximation, site 3 also supports this hypothesis. Again, site 2 was much higher than the other two sites, with an origination date of 163.0 years ago and does not support the hypothesis.

Hypothesis 2, which states that valley floor gully erosion rates will obey the Rate Law (Graf 1979), demonstrating a reduction in headward extension rates through time as network extension reduces drainage area, was contradicted. This may be explained through the complex interplay of multiple controls on erosion rate, including drainage basin area, slope of the valley, and the sinuosity of the gully. Another possibility is that an up-valley decrease in sediment thickness, and thus reductions in total erosion needed for headwall migration could offset loss of water flow due to diminished drainage area. It was found that the erosion rates are different for each gully, so while the method of sampling and counting tree root rings does prove to be an accurate method to estimate gully headward erosion rate it would need to be done at each individual site to produce accurate individual results for each gully, i.e., results from these sites cannot be easily extrapolated to other Piedmont locations without further information of erosion rate controls.

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APPENDIX A: LANDFORM DEFINITIONS

Upland gully – a deeply incised V- or box-shaped trench eroded into upland regolith (residual soil and saprolite, +/- colluvium) usually initiated under former agricultural conditions with poor land management. Upland gullies may be individual or multi-fingered (a.k.a., digitate) to form a gully network.

Gully fan – a fan-shaped mass of colluvium and/or alluvium ("coalluvium" of Schaetzl (2015)) located downslope of an upland gully mouth. Contours will be convex downslope on the fan surface.

Valley sediment fill – a mass of sediment, a combination of alluvium and colluvium, that fills a valley floor creating a broad flat or gently undulating surface that slopes towards local base level (often a floodplain or beaver pond at RT Preserve).

Valley floor gully – a gully-like (incised/entrenched) channel, often carrying perennial water flow (at RT Preserve), that is eroded into valley sediment fill deposits. Although these may carry perennial flow, they are distinguished from a stream channel in that their cross-sectional form is controled by rapid and deep incision, and mostly unrelated to either baseflow or flood flow stages.

Knickpoint - a distinct vertical or near vertical drop along a stream channel or gully bed potentially produced by multiple mechanisms including resistant rock, saprolite, or cohesive soil "outcrops" and/or rapid drops in local base levels.

Knick zone – same as a knick point, except the drop is spread out over a greater distance along the stream channel.

Seepage head – a distinct vertical or near vertical gully-like headcut produced primarily by seepage failure along a subsurface flow path. Accordingly, there should be no well defined surface water channel (dry or wet) feeding to the lip of the headcut, and the lip (edge) of the head usually lies at or near the general elevation of the valley floor. Seepage heads may be lateral (initiated on a gully bank) or longitudinal (forming the head of a larger valley floor gully).

Seepage knick – like a seepage head except, shallowly channeled overland flow erosion may also be contributing substantially to headcut development and extension at the lip. The lip (edge) of the head knick lies below the general elevation of the valley floor, and the shallow channel feeding it has well-defined banks.

Soil pipe – a conduit-like cavity lying beneath the ground surface and formed by the hydraulic excavation and connection of large secondary pores (macropores) such as root cavities and animal burrows. Soil pipes are often found on upland gully banks where water infiltrating downward from the flat just beyond the bank top emerges from the bank face. Sometimes used as a synonym for “tunnel” in the literature (but see the definition of tunnel herein)

Tunnel – a conduit-like cavity lying beneath the ground surface and excavated within valley fill sediments at the face of a seepage head or knick, where high water pore pressures from subsurface flow concentration weaken and dislodge sediment. Tunnels are typically of larger diameter than pipes and grow headward to variable distances until their roofs collapse, transforming them into surface channels or gullies.