Effects of Landslide Disturbance on Soil and Vegetation in a Steep Landscape in Central Virginia

Abigail Mary Ackerman
Herndon, Viginia

B.A. Geology, Bryn Mawr College, 2017

A Thesis presented to the Graduate Faculty of the University of Virginia in Candidacy for the Degree of Master of Science

Department of Environmental Sciences

University of Virginia

May 2025

Committee: Ajay B. Limaye (Chair), Lawrence E. Band, Justin B. Richardson

Contents

This manuscript is in preparation for submission to *Journal of Geophysical Research: Biogeosciences* as "Effects of Landslide Disturbance on Soil and Vegetation in a Steep Landscape in Central Virginia" by A.M. Ackerman, C.A. Copenheaver, J.B. Richardson and A.B. Limaye.

Abstract

In the central Appalachian Mountains, landslides and debris flows are major geomorphic agents and natural hazards. A prominent example occurred in 1969, when the remnants of Hurricane Camille triggered over 150 debris flows in Fortune's Cove, a first-order drainage basin in Nelson County, Virginia. These debris flows stripped colluvium and trees from hollows, yet the landscape responses are incompletely understood. To address this gap, we surveyed three hollows in Fortune's Cove to determine the geomorphic context for debris flow initiation and to compare soil depth and woody plant communities between areas impacted by historical debris flows and undisturbed reference sites. Soil regeneration was spatially heterogeneous: some disturbed sites showed predominantly exposed bedrock (<2 cm soil) while others had soil profiles >10 cm thick; soils at undisturbed sites were all >80 cm thick. Vegetation surveys showed distinct composition and structure between the disturbed and reference sites: Sweet birch (*Betula lenta*) and tuliptree (*Liriodendron tulipifera*) dominated the overstory at disturbed sites, while tuliptree, sassafras *(Sassafras albidium*), and snags dominated the reference sites. Topographic analysis indicates that for the same slope, the transition between the signatures of hillslope and fluvial erosion processes occurs at much lower drainage areas (10^3 to 10^4 m^2) compared to drier, less vegetated areas from other studies (10^5 to 10^6 m^2). This case study suggests that debris flows cause persistent changes to soils and forests, which can inform land management practices in the context of precipitation changes in the Appalachian region driven by global climate change.

Plain Language Summary

Debris flows, a fast-moving type of landslide, are a recurring phenomenon in the eastern US. Common after heavy rainfall, a debris flow can strip all the soil and trees off a hillside, posing hazards to infrastructure and people in its path. However, uncertainties persist about how the soils and plants return, which may affect when the next debris flow occurs. To better understand links between debris flows, forests, and soils, we used a field study in Virginia to compare forests and soils in sites disturbed by debris flows to nearby forests and soils that were left intact. We found that the forests and soils in debris flow scars were distinctly different from those in intact forests, and that these debris flows start from smaller drainage areas than ones in California. These results can inform efforts to manage landscapes as climate change impacts rainfall patterns in the Appalachian region.

1 Introduction

Debris flows are episodic, fast-moving mass movements. A fundamental process of sediment movement in steep landscapes, debris flows happen when the forces holding sediment in storage in steep, unchanneled uplands are overcome by forces that would move them to lower channels (Coussot & Meunier, 1996; Iverson, 1997; Stock & Dietrich, 2006). A global phenomenon, debris flows reshape landscapes, disturb ecology, disrupt infrastructure, and pose major hazards (Cui et al., 2024; Imaizumi et al., 2006; Kean et al., 2013; Piciullo et al., 2018; Ramos Scharrón et al., 2012; Restrepo et al., 2009; Stock & Dietrich, 2003; Wang et al., 2020). In the central Appalachian region of the United States, disasters following rainfall-initiated debris flows cost money and lives (Eaton et al., 2003b; Williams & Guy, 1973; Wooten et al., 2016). The complex web of interactions between vegetation, soils, subsurface hydrology, climate, and history of past debris flows all shape rainfall-initiated debris flows in this region (Hwang et al., 2015; McGuire et al., 2023; Mirus et al., 2019; Parker et al., 2016). However, as these boundary conditions change due to climate change and other environmental stressors, it is unclear how debris flow initiation and recovery in the region will likewise respond to these changes (Stoffel et al., 2024).

Numerous studies of debris flow initiation focus on the western United States (Gabet & Dunne, 2002; Iverson, 2000; Iverson et al., 1997; Jakob et al., 2005; Kean et al., 2013; Stock & Dietrich, 2003; Whipple & Dunne, 1992). In comparison, the Appalachian region differs in several key respects related to debris flow initiation and the responses of soils and vegetation. The Appalachian region has a humid climate, more heavily weathered bedrock, is less tectonically active, and generally has deeper soils and denser vegetation — as such, multiple studies have proposed that debris flows in the eastern United States have different patterns of initiation and recovery than other regions (Parker et al., 2016; Wooten et al., 2016). Understanding how these environmental variables interact and which, if any, are more important controls on debris flow mobilization is essential to improving hazard assessment approaches for the eastern United States and complementing ongoing efforts for landscapes shaped by wildfires in the western United States (Cannon et al., 2011).

In the central Appalachian region, the most common initiation mechanism for debris flows and landslides is heavy rainfall, which increases pore pressure in soil-mantled hollows where subsurface flow pathways converge (Iverson, 2000; Parker et al., 2016). One of the most impactful examples occurred in 1969, when the remnants of Hurricane Camille poured up to 28 inches of recorded rainfall in just eight hours in Nelson County, Virginia (Smith et al., 2011), initiating thousands of debris flows across the county, causing severe floods, creating millions of dollars' of damage to infrastructure and property, and killing 150 people (Smith et al., 2011; Williams & Guy, 1973). There were over 150 debris flows in Fortune's Cove — a small catchment in Nelson County — which denuded every hollow (Williams & Guy, 1973). In 1979, researchers surveyed vegetation on debris flow scars near Fortune's Cove, finding early- and mid-successional forest compositions 10 years after the storm, and between 20-100% vegetation cover at some sites (Hull & Scott, 1982).

In humid climates, vegetation can determine both the legacy and future risk of debris flows (Hack & Goodlett, 1960; Osterkamp et al., 1995; Restrepo et al., 2009). The presence and variety of vegetation on steep slopes can alter subsurface flow pathways, soil saturation, and holding capacity during heavy precipitation (Band et al., 2012; Hales & Miniat, 2017; Hwang et al., 2015; Sidle & Bogaard, 2016), impacting slope stability. In this context, vegetation can both stabilize hillslopes and drive erosion (Hales & Miniat, 2017; Hwang et al., 2015; Restrepo et al., 2009; Sidle & Bogaard, 2016). Therefore, characterizing patterns of vegetation in disturbed hollows compared to undisturbed hollows and the spatial relationship between debris flows and woody plant communities may provide insight into some of the ecological processes that control post-debris flow landscape recovery and make the new pre-debris flow landscape.

Vegetation in the central Appalachians likely impacts both debris flow initiation and post-debris flow recovery in ways not currently accounted for in our understanding of landscape evolution in this region by potentially altering the distribution of debris flows and certain plants across a landscape (Hwang et al., 2015; McGuire et al., 2023; Mirus et al., 2019; Parker et al., 2016; Restrepo et al., 2009). As climate change potentially increases the intensity of extreme precipitation events (Balaguru et al., 2023; Nieto Ferreira et al., 2018) and alters regional ecological succession dynamics (van Breugel et al., 2024; Prach & Walker, 2019), there is a critical need to improve forecasts for how vegetation dynamics interact with debris flows. This study tests: 1. How vegetation and soil differ between sites disturbed by the 1969 debris flows and undisturbed reference areas, and 2. How the location of debris flow mobilization relates to the geomorphic context of central Appalachia, and whether the critical drainage area defining debris flow regimes in this region varies systemically compared to valleys in other parts of the United States.

This manuscript is organized as follows. Section 2 reviews potential responses of vegetation and soils to disturbance generally, and in the context of disturbance by debris flows. Section 3 details the study design and is followed by results for vegetation surveys (Section 4), soil analysis (Section 5), and topographic analysis (Section 6). Section 7 distills implications for debris flows and landscape response in the central Appalachian region.

2 Patterns of soil and vegetation response to debris flow disturbance

Following hillslope disturbance, several processes can cause spatially heterogenous recovery of soils and vegetation. While mineral and vegetative soils are often completely removed from areas disturbed by a debris flow, these areas can be surrounded by undisturbed, mature forest. Therefore, ecological succession in disturbed areas does not follow a strict primary-or secondary-succession model and instead is a spatially heterogenous combination of the two (Freund et al., 2021; Restrepo et al., 2003; Walker & Shiels, 2013). Edge instability of remaining soils at the sides of a debris flow scar can persist for years, delaying biological succession because many vascular plants require stability to grow (Walker et al., 2009), or altering species composition by selecting for plants that tolerate less stable substrate (Freund et al., 2021; Restrepo et al., 2009). However, continued edge infill from mature forest soils, along with materials from unstable edges upslope concentrated in the hollow and litterfall from mature trees, can hasten soil generation compared to primary succession following other disturbances (Cenderelli & Kite, 1998; Ramos Scharrón et al., 2012; Restrepo et al., 2009; Schomakers et al., 2017; Walker & del Moral, 2003). While litterfall can replenish organic materials for soil formation near to and downslope of a tree, proximity to remaining mature forest in the topographic low of a hollow can also inhibit new plant growth or alter species composition. The partially closed canopy surrounding the disturbed zone may favor succession by more shade-tolerant, evergreen, and/or fast-growing species (Desta et al., 2004; Walker & Shiels, 2013).

Surface- and ground-water concentration and persistence in the center of the hollow can also change soil texture and plant diversity. While gravity does move material — e.g., sediment and litterfall — towards the topographic lows at the central axes of denuded gullies, it also concentrates surface- and groundwater through these lows and preferentially moves smaller particle sizes out of the gully, leaving larger ones behind (Cenderelli & Kite, 1998). Generally, larger particles and fragments have higher infiltration rates and lower available water holding capacities (Libohova et al., 2018; Lv et al., 2021), but presence of organic matter can increase available water capacity (Libohova et al., 2018). Water availability in turn controls plant species diversity (Stephenson & Mills, 1999) and belowground biomass (Deljouei et al., 2023; Hales & Miniat, 2017), which control slope stability through root cohesion (Gabet & Dunne, 2002; Hwang et al., 2015). Roots of plants in the persistently wetted zone of the hollow have also been found to be weaker than their side slope and spur ridge counterparts (Hales et al., 2009).

Over the past one hundred years, deciduous forests in the eastern United States have undergone several regime shifts, such as fire suppression (Abrams & Nowacki, 1992; Brose et al., 2001; Lafon et al., 2017), loss of keystone canopy species (Ford et al., 2012a; Paillet, 2002; Vandermast & Van Lear, 2002), and climate-change related succession (Elliott & Hewitt, 1997), happening concurrently with succession due to episodic events such as debris flows. Great laurel (*Rhododendron maximum*), a dense evergreen shrub, has become widespread in the central and southern Appalachians (Dudley et al., 2020; Wooten et al., 2016) following the disappearance of canopy-height American chestnut trees (*Castanea dentata*) in the early 1900s. Because of its dense, year-round foliage, great laurel can inhibit recruitment of seedlings and growth of deciduous understory plants (Vandermast & Van Lear, 2002), reducing forest diversity. Several studies in North Carolina have noted that its shallow, comparatively weaker root system (Hales et al., 2009) could potentially lower the shear failure threshold for debris flow initiation (Wooten et al., 2016). Characterizing debris flow-related succession in the context of these larger scale ecosystem dynamics is imperative for improving predictions for how debris flows and vegetation interact to shape the landscape. Specifically, looking at Virginia forests that have experienced debris flow disturbance within the last century will allow us to contextualize landscape response to debris flows under current regional hydroclimate conditions.

3 Study site and methods

3.1 Study site

To examine the relationships between vegetation, soils, and geomorphology in the central Appalachian region, we focus on Fortune's Cove, an exemplar site shaped by debris flows and disturbed within the last century. Fortune's Cove is a first-order drainage basin in Nelson County, Virigina, owned by the Nature Conservancy as a preserve since 2002 (Figure 1). Fortune's Cove is situated on the border between the Piedmont and central Blue Ridge physiographic provinces of Virginia and underlain by the Grenville-age (1.1 to 1.0 Ga) Lovingston massif, a unit composed of highly foliated gneissic rocks metamorphosed to lower granulite-amphibolite facies (Evans, 1991).

The bedrock on the west side of Fortune's Cove is primarily middle-Proterozoic porphyroblastic biotite-plagioclase augen gneiss, while the east side is middle Proterozoic layered biotite granulite and gneiss. Surficial geology in Nelson County has not been extensively mapped, but is largely saprolite and colluvium weathered from the bedrock under a temperate-humid climate over the past 10,000 years (Whittecar & Ryter, 1992). Bedrock is typically buried beneath regolith whose thickness varies from a few centimeters up to 10 m (Williams & Guy, 1973). The slopes within hollows are steep and densely covered by trees, bushes, and smaller groundcover plants (Williams & Guy, 1973).

3.2 Study design

Fortune's Cove provides a unique opportunity to study landscape response to debris flows 55 years post-disturbance, with a focus on vegetation and soil recovery. To do so, we selected a total of 18 sites — nine paired plots — on the northwestern and western edges of Fortune's Cove to survey vegetation communities and soil composition of sites disturbed by the 1969 debris flows with undisturbed reference sites. We selected sites using a 1-meter bare-earth topographic DEM of Fortune's Cove (U.S. Geological Survey, 2015) created from airborne lidar data collected under the USGS 3D Elevation Program (Arundel et al., 2015). We determined the locations of the 1969 debris flow headscarps using an existing survey from the Virginia Division of Geology and Mineral Resources landslide inventory(Carter-Witt & Whitehead, 2019).

To capture a variety of slopes, aspects, and distances to ridgeline within both disturbed and reference sites, sites were chosen to adjacent hollows on the western side of in Fortune's Cove and, as much as possible, avoid recent human disturbances such as trail maintenance and clearcutting for power line access (Figure 2). Sites are named according to hollow (1, 2, 3), longitudinal position within the hollow (top, mid, base), and whether the site is disturbed or a reference site (D, R) (Table 1).

To distinguish vegetation surveys between disturbed and undisturbed areas, we require a consistent approach to delimiting these areas. Therefore, we created a buffer centered on the debris flow paths for hollows within all of Fortune's Cove. We set the width of the buffer to 10 m, based on measurements of the width of debris flow chutes from the 1969 debris avalanches in nearby Polly Wright and Wills coves (Williams & Guy, 1973) and evidence from modern topography at Fortune's Cove. We refined the bounds of reference plots for undisturbed sites based on field observations — i.e., areas with larger trees and intact soil profiles outside of obvious scour zones. Each pair of disturbed and undisturbed sites occurs within the same hollow, except for hollow 1. At that location, the extreme topographic slope and narrowness of the hollow made locating an undisturbed site infeasible. Therefore, sites 1Dmid/1Rmid are in a different hollow from 1Dbase/1Rbase and 1Dtop/1Rtop.

3.3 Vegetation surveys

In July 2024, we conducted vegetation surveys by identifying over-, mid-, and understory plants in our selected plots. Within each of the 18 sites, we established a 200 m^2 overstory vegetation plot, where we measured diameter at breast height (DBH, 1.37 m above the root collar) and identified genus and/or species for all trees >10 cm DBH. Nested within the overstory plot was an 80 m^2 midstory vegetation plot, located on the uphill edge of the overstory plot, where we identified and measured DBH for all saplings (trees <10 cm DBH and taller than 1.37 m). Lastly, nested within the midstory vegetation plot was a 32 m^2 understory vegetation plot where we identified and counted all seedlings and shrubs < 1.37 m tall (Figure 2).

3.4 Soil surveys

We conducted soil sampling outside of the upper boundary of the nested vegetation plots, digging with shovels until bedrock or until we reached 20 to 25 inches depth, and collecting samples from each identifiable horizon, starting with the deepest horizon to reduce potential cross-contamination from soil in upper horizons falling into the bottom of the soil pit. In total, we collected 46 samples across 18 sites. We analyzed physical and chemical characteristics using methods similar to those described by Rice et al. (2024). For each sample, we analyzed soil texture, percent organic matter, percent base saturation, and elemental concentrations. For texture, we soil samples passed through a 2 mm sieve and recoded the fractions of sand (< 2 mm to 63 µm), silt (63 µm to 2 µm), and clay (< 2 µm) by weight. After digesting samples, we measured soil element concentrations using Agilent 5110 Inductively Coupled Plasma-Optical Emissions Spectrometer (ICP-OES; Agilent, Santa Clara, CA, USA). After we standardized elemental concentration to mass per mass of soil, we estimated cation exchange capacity by estimating the milliequivalents (meq) of exchangeable cations and then calculated base saturation by taking the sum of the base cation (Ca, Mg, K, Na) concentration divided by each element's charge and dividing by the cation exchange capacity.

3.4 Statistical analysis

To assess differences in plant communities in Fortune's Cove, we calculated importance values for all woody species in the under-, mid-, and overstory of debris flow sites and reference sites. Importance values for overstory and midstory species were calculated as an average of relative frequency, or how many plots in which a species appeared; relative density, or how many stems of a species we found per unit area; and relative dominance, or how much basal area a species took up across all plots. Because we did not measure DBH in understory species, importance values for the understory were calculated as an average of relative frequency and relative density only.

We also used non-metric multidimensional scaling (NMDS) to develop an ordination of the similarities in overstory tree species distributions relative to several environmental variables. NMDS is a distance-based ordination technique that can be used to assess similarities and differences between sets of sites with shared environmental variables, as well as how strongly those variables correlate with community changes (Haugo et al., 2011; McCune & Grace, 2002). For each survey plot we considered geomorphic status (disturbed or undisturbed), hollow (1, 2, 3), longitudinal location of the site (top, mid, base), elevation (minimum, maximum, mean), slope (minimum, maximum, mean), and mean aspect (Table 1). We constructed an NMDS plot using the Bray-Curtis dissimilarity index of overstory species at each site location with minor species — i.e., those that only occurred in a single plot — removed and all oak and hickory species combined into genus-level categories.

3.5 Topographic signature of debris flows in the landscape

Numerous studies on the relationship between hillslope erosion and fluvial erosion in steep channel networks have identified a power law scaling relationship between topographic slope and drainage area (McGuire et al., 2023; Montgomery et al., 2009; Neely & DiBiase, 2023; Roering et al., 2007; Stock & Dietrich, 2003). The most common equation for this power law for bedrock channels is

$$S = \frac{S_0}{1 + a_1 A^{a2}} \tag{1}$$

where S is the slope, A is upstream drainage area, and S_0, a_1, and a_2 are empirical coefficients. Throughout the longitudinal profile of a steep hollow, where hillslope processes dominate, topographic slope is relatively constant for small drainage areas. A scatter plot of slope versus drainage area typically shows a rollover point at a critical drainage area, after which topographic slope begins decreasing as drainage area increases (Montgomery & Dietrich, 1988; Neely & DiBiase, 2023; Stock & Dietrich, 2003, 2006). This rollover point (A_{cs}) represents the transition zone between colluvial channels and concave-up fluvial channels (Neely & DiBiase, 2023) and is calculated from the empirical coefficients in Equation 1 as follows

$$A_{cs} = a_1^{-1/a_2} \quad (2)$$

This transition zone is also considered the point at which debris flows, rather than regolith creep or fluvial erosion, act as the dominant erosional process (McGuire et al., 2023; Neely & DiBiase, 2023; Stock & Dietrich, 2003).This rollover point can occur at different thresholds in different climates and hydrologic regimes (Montgomery & Dietrich, 1988), and has not been previously characterized for steep landscapes in in the region of the study site.

To calculate the rollover point for Fortune's Cove, we estimated the extent of hollows and channels using topographic data. We used standard flow-routing approach to generate a channel network from a 300 m^2 drainage area threshold on the DEM of Fortune's Cove (Tarboton et al., 1991). Next, we sampled slope and drainage area every 5 m along the channel, from the channel head to the valley floor. We repeated this process for nearby sites where Hull and Scott (1982) conducted similar vegetation surveys, including Freshwater Creek (FRESH), Davis Creek and Tributary site (DAV), and Wills Cove (WILLS) in addition to Fortune's Cove (FORT) (Figure 3). The topographic data for each site reflect landscape form following debris flow erosion in 1969. Therefore, we assume that this disturbance caused negligible change to drainage area and overall topographic slope at the sites of debris flow initiation.

We extracted slope and area at each of these points and grouped the data into 100 logarithmically spaced bins by drainage area for each catchment and calculated the mean slope and drainage area for each bin. Because the empirical coefficient S_0 represents the behavior of the channel slope at low drainage areas, we set S_0 to be equal to the maximum binned mean slope of each cove. We then plotted these binned data to calculate the coefficients a_1, a_2, and A_{cs} from equations 1 and 2 using a nonlinear least squares regression model.

4 Effect of landslide disturbance on vegetation communities

4.1 Importance values for forest species

The results of the vegetation surveys between disturbed and undisturbed reference sites showed several compositional differences across forest layers. The total species richness (number of species) did not show a substantial difference between of the debris flow sites (n = 36) compared to the reference sites (n = 37). However, the species richness in the overstory canopy layer was higher at the reference sites (n = 13) compared to the debris flow sites (n = 8). At the debris flow sites, we found four non-native species: tree of heaven (*Ailanthus altissima*), autumn olive (*Elaeagnus umbellata*), princesstree (*Paulownia tomentosa*), and multiflora rose (*Rosa multiflora*). The reference sites also had four non-native species: tree of heaven, autumn olive, multiflora rose, and Japanese honeysuckle (*Lonicera japonica*).

The most important species in the understory at the debris flow sites (Table 2) were spicebush (*Lindera benzoin*), sassafras (*Sassafras albidium*), and Virginia creeper (*Parthenocissus quinquefolia*). Of these three species, only sassafras has the potential to develop into an overstory tree. The most important understory species at the reference sites were sassafras, green ash (*Fraxinus pennsylvanica*), redbud (*Cercis canadensis*), and spicebush. Sassafras was present in all plots.

The most important species in the midstory at the debris flows sites were sweet birch, spicebush, and red maple (*Acer rubrum*). Notably, at this site two shrubs had unusually high densities: spicebush had 597 stems/ha, and bladdernut (*Staphylea trifolia*) had 264 stems/ha. The most important species in the midstory at the reference sites were sassafras and red maple. Sassafras had an unusually high density, with 653 stems/ha. Red maple and snags — standing dead trees — both had a density of 264 stems/ha.

The most important species in the overstory at the debris flow sites were sweet birch (*Betula lenta*) and tuliptree (*Liriodendron tulipifera*). Sweet birch was widespread in its distribution, had a high number of stems, and many of the trees were large. Sweet birch occurred in all plots, and the largest tuliptree was 45.2 cm DBH. The most important species in the overstory at the reference sites were tuliptree and sassafras. The density of tuliptree in the reference sites was 200 trees/ha and sassafras occurred in 78% of the plots. Snags were also an important component of the overstory at the reference sites, with the largest snag measuring 69 cm DBH.

Great laurel dominance is expanding in the Blue Ridge region within the central Appalachians (Dudley et al., 2020; Vandermast & Van Lear, 2002; Wooten et al., 2016), Yet we found no evergreen rhododendrons throughout this survey. Out of the 3,600 m^2 surveyed on the west side of Fortune's Cove, we recorded only one evergreen ericaceous shrub: a single understory mountain laurel (*Kalmia laitfolia)* at site 3Dmid.

4.2 Site similarity based on species and environmental variables

The non-metric multidimensional scaling (NMDS) indicates a compositional difference between the debris flow sites, located on the left side of the ordination plots, and the reference sites, located on the right side of the ordination plots (Figure 4). Only geomorphic status — whether a site is disturbed or undisturbed reference site — is a significant control on vegetation similarity at surveyed sites (R^2 = 0.94, P < 0.01). Although many other studies have noted slope and aspect as controls on vegetation distribution and diversity within cove forests (Cui et al., 2024; Desta et al., 2004; Stephenson & Mills, 1999), neither were significant controls on dissimilarity ($R^2 \leq 0.03$, P < 1).

5 Effect of landslide disturbance on soils

The soils within disturbed and undisturbed reference sites varied both in space and texture. Soil regeneration was spatially heterogeneous, with some disturbed sites showing >10 cm soil thickness while others had <2 cm thickness and were either Entisols or exposed bedrock. Comparatively, undisturbed soils were >80 cm thick. Channery Dystrudepts — acidic, low fertility soils common in humid regions — suggesting potential soil mass loss. The site with the least recovery in soil depth was site 1Dtop: depth-to-bedrock was 10 cm, 40 cm less than soil depth at site 1Rtop. In contrast, site 1Dmid had a similar soil depth (approximately 48 cm) compared to site 1Rmid. Across all samples taken at all sites — i.e., not weighted based on the size of the horizon from which the sample was taken — the samples are primarily composed of sand, with smaller percentages of clay and silt (Figure 5).

Notably, several reference site samples have higher percentages of clay than all other samples, and, like vegetation plots, also do not follow a consistent trend based on longitudinal position within the hollow. However, using soil composition as an environmental variable in NMDS analysis did not show significant groupings on similarity based on any soil environmental variables — texture, percent carbon, or elemental concentration. While soil depth regeneration was uneven, across all samples, there is no consistent difference in macronutrient or carbon content between debris flow and reference sites (Figure 6).

6 Topographic context for debris flow scars

Our study surveyed vegetation in Fortune's Cove 55 years post-Camille, while Hull and Scott (1982) surveyed vegetation in nearby Davis/Tributary Creek, Freshwater Creek, and Wills Cove 10 years post-Camille. To better understand the topographic context for debris flow scars from Camille locally, and how that context may relate to vegetation cover, we analyzed slope-drainage area relationships for these four sites. Within Fortune's Cove, Davis Creek, Freshwater Creek, and Wills Cove, A_{cs} values — the drainage area at which the behavior of the line of best fit according to equation 1 varies from $A_{cs} \approx 5.17 \times 10^3$ m^2 (Davis/Tributary) at smallest to $A_{cs} \approx 2.47 \times 10^4$ m^2 (Fortune's Cove) at largest (Figure 7). All lines fit with equation 1 use an S_0 value equal to the maximum binned mean slope of each cove and have an R^2 value of > 0.93 (Table 3). This variation indicates differences in the drainage area for a shift from predominantly colluvial to fluvial erosion processes across these sites.

The debris flow headscarps occur in areas of highest topographic slope in Fortune's Cove and low ($<10^3$ m^2) drainage areas. The average slope at debris flow headscarps is consistently higher than average slope at comparable drainage areas for the rest of the channel network. The greatest drainage area at which a debris flow headscarp is found is 2.7×10^3 m^2, in Freshwater Creek — almost a full order of magnitude smaller than the empirically derived transition point.

7 Discussion

7.1 Vegetation change, 1979 to 2024

Between sites we surveyed and nearby sites surveyed in 1979, there are several key community differences that point to shifts in forest composition in multiple stages after Hurricane Camille. The importance value results in Fortune's Cove differ from those of the vegetation surveys performed by Hull and Scott (1982) in the Davis Creek/Tributary, Freshwater Cove, and Wills Cove debris avalanche and reference forest sites. While their study grouped all saplings and trees with DBH into one category, making no distinction between midstory and overstory plants, the most important species at all disturbed sites were sweet birch, tuliptree, and black locust (*Robinia pseudoacacia*) (Hull & Scott, 1982). The three most important reference forest trees were blackgum (*Nyssa sylvatica*), red maple, and black oak (*Quercus velutina*) at the Tributary forest site and chestnut oak (*Quercus montana*), red maple, and tuliptree at the Davis Creek forest site. The study also reports seeing a high density of vines, which may have been responsible for trapping soil and regolith in debris avalanche scars, aiding in soil retention as denuded hollows began filling in with soil from edges or uphill (Hull & Scott, 1982).

Hull and Scott (1982) hypothesized that, as succession continued, the early successional species with high importance values across all sites that thrived in open canopy conditions — namely, black locust, sweet birch, and sassafras — would fail to thrive as the canopy filled in post-disturbance (Hull & Scott, 1982). However, while this does appear to be true for black locust in Fortune's Cove, which we only found in the understory, sweet birch and sassafras were prolific across debris flow and reference sites. Sweet birch was the most important species in the overstory and midstory at disturbed sites, while sassafras ranks fifth at both, compared to the complete lack of black locust. It also does not appear that introduced nuisance species such as tree of heaven were able to use the disruption to establish themselves and gain dominance in Fortune's Cove; another prediction for post-Camille forests (Hull & Scott, 1982).

One key difference between the current forest composition in Fortune's Cove and the forest compositions in 1979 is the comparative lack of oaks. While oaks were the most important species in the reference forest overstory in 1979, there were no mid- or overstory oaks in debris flow sites in Fortune's Cove, and there were overstory — no midstory — oaks observed in reference forests. In addition to increased browsing of oak seeds and seedlings by animals, one other factor driving this shift may be the mesofication of the forest environment (Alexander et al., 2021; Brose et al., 2001). Fire exclusion in Eastern forests as well as climate change-induced increases in precipitation may be favoring other, more mesic species above oaks, even in post-debris flow forests (Alexander et al., 2021).

7.2 Relationships between vegetation, soils, and topography

Unlike vegetation, for which there were distinct compositional differences between disturbed and undisturbed forests, soils in Fortune's Cove vary spatially with respect to individual cove and position relative to the channel head. Some disturbed sites recovered more than 30 cm soil while others less than 8 cm, and there was no consistent pattern to the soil depth anomaly between disturbed and undisturbed sites across all pits. The high degree of local variation within relatively small areas is consistent with past studies of debris flow soil disturbance (Montgomery et al., 2009) and past surveys of regolith cover in the region (Williams & Guy, 1973). This may suggest that more topographic factors influence soil regeneration than just disturbance history, such as bedrock features that trap soil to stop or slow further gravity-driven particle movement. This could also point to the determinative role the extent of initial denudation has on post-debris flow recovery, as others have hypothesized (Hull & Scott, 1982).

The degree of soil recovery — depth, texture, and nutrients — is an important consideration for which species can establish themselves on the debris flow scars. The two most important overstory species on the debris flow sites, sweet birch and tuliptree (Table 2), germinate through seeds (Burns & Honkala, 1990), suggesting that mature trees in the surrounding forest act as sources for seeds once soils recovered enough depth post-debris flow. Previous research has noted that soil physical characteristics are likely more important controls than chemical characteristics with tuliptree growth (Burns & Honkala, 1990), meaning that the sandier textures of Fortune's Cove may be facilitating tuliptree dominance.

Soil characteristics respond to hydroclimatic setting, such that soils are able to drain a water from a typical rainfall event while also storing or retaining enough water to support vegetation (Mirus et al., 2019). Vegetation that grows on post-disturbance soils may then stabilize soil and indicate how soil water storage capacity develops after the disturbance event,. Previous studies of sweet birch and tuliptree in North Carolina have found that, while sweet birch has generally higher root tensile strength than tuliptree, once adjusting for this species effect, there was no correlation between root tensile strength and topographic position, maximum slope, and drainage area for either species (Hales & Miniat, 2017). However, this study did find that root tensile strength decreased with increasing soil moisture. The primarily sandy soils of Fortune's Cove (Figure 5) may have higher infiltration rates and lower available water holding capacities due to particle size (Libohova et al., 2018; Lv et al., 2021), that could potentially allow for higher saturation during heavy rainfall. The relationship between soil texture and root tensile strength, and therefore root reinforcement of slopes post-disturbance in this region, merits further study.

7.3 Comparison of vegetation, soil, and topographic observations with debris flows in the central Appalachians and western United States

Soil depth and plant roots are important to controls on vulnerability to debris flow disturbance (Montgomery et al., 2009; Parker et al., 2016). The shallowness of soils following disturbance is likely more favorable to laterally rooting species. Moreover, the sunlight-limiting effects of surrounding mature trees to the debris flow scars favor species which are shade-tolerant, or which can seed prolifically and grow fast enough to exclude other species. In some cove forests of the central Appalachians, these factors have led to the proliferation of great laurel over other species (Brose, 2016; Dudley et al., 2020; Van Lear et al., 2002), to the detriment of slope stability (Hales et al., 2009; Wooten et al., 2016). However, our study found no great laurel in Fortune's Cove, in disturbed or reference forests. Taken with the historical record of vegetation in nearby disturbed and undisturbed cove forests, which also recorded no great laurel (Hull & Scott, 1982), it is likely that the lack of great laurel in Fortune's Cove is due to other regional factors impacting its establishment, not disturbance history.

The drainage area at which a landscape transitions between predominantly hillslope and fluvial erosion processes, A_{cs}, varies greatly between the central Appalachian catchments and studies on sites with comparable slopes in the western United States. The A_{cs} values for nearby hollows in Fortune's Cove, Davis Creek, Freshwater Creek, and Wills Cove are orders of magnitude smaller than catchments in the San Gabriel or Northern San Jacinto Mountains (Table 3). The wet climate and lack of tectonic uplift in the Appalachian region causes relief at topographic steady state compared to mountains in the California Transverse Ranges (Whipple, 2009), although slopes at debris flow initiation sites are comparable. Eaton et al. (2003b) suggested that debris flows account for half the long-term denudation in this region. Because the critical drainage area A_{cs} represents the threshold at which debris flows act as the main erosive agent as a channel transitions between colluvial and fluvial processes, it is possible that this transition at lower drainage areas reflects the large role debris flows play in driving long-term landscape evolution compared to other sediment transport mechanisms. We speculate that in the modern climate, this predominance of debris flow erosion could be related to the heavy vegetation in this region: vegetation can generate and trap soils or larger sediment particles, as well as stabilize slopes at steeper angles, increasing colluvium supply until it can be moved by a high magnitude event (Parker et al., 2016).

7.4 Implications for future hazards

The timescale of the vegetation and soil recovery following a debris flow reflects the landscape's vulnerability and resilience to these hazards. A landscape is considered vulnerable to hazards when recovery time is longer than the return period of the triggering storm events (Mirus et al., 2019). For a landscape to be considered resilient to rainfall-initiated debris flows, it must recover faster than the recurrence interval of debris flow events (Mirus et al., 2019). For this region, the timescale of debris flow recurrence for any individual hollow is on the timescale of 2.5 to 3 ka since the onset of the Wisconsinan glacial maximum (Eaton et al., 2003a; Eaton et al., 2003b; Parker et al., 2016), although the return period of storms capable of triggering debris flows may be shorter (Smith et al., 2011). In Fortune's Cove, based on the degree of soil and vegetation recovered, 55 years after Hurricane Camille triggered debris flows across the region, it is reasonable to predict, that hydrologic and vegetation recovery will outpace the recurrence interval of debris flows if past patterns hold. However, it is unclear if past patterns will hold as the regional hydroclimate climate changes (Nieto Ferreira et al., 2018; Parker et al., 2016; Stoffel et al., 2024).

The vulnerability of the forests on debris flow sites is based not just on the recurrence of debris flows, but on stressors such as pests (Ford et al., 2012b), disease (Paillet, 2002; Vandermast & Van Lear, 2002), climate (Alexander et al., 2021; Brose et al., 2001; Dudley et al., 2020), human activity (Hales, 2018; Lafon et al., 2017) and interspecies competition (Brose, 2016; Van Lear et al., 2002). A mixed forest that is resilient to these stressors is more likely to stabilize slopes, but as forest diversity decreases or the ecosystem transitions from forest to another land cover, root reinforcement of soils is likely to decrease (Hales, 2018). Compared to the reference forest overstory, the debris flow overstory had lower species richness: $n = 8$ for debris flow sites compared to $n = 13$ for reference sites. The lower species richness could make debris flow sites more vulnerable to the impacts of outside stressors and decrease slope stability if dominant species change, as is occurring for slopes in North Carolina dominated by great laurel (Ford et al., 2012a; Hales et al., 2009). How changes to the forest, and therefore changes to root reinforcement, may impact the recurrence interval of debris flow events in this region is an important area for future research.

8 Conclusions

A survey of forest and soils a site in the central Appalachians disturbed by widespread debris flows in 1969 indicates distinct compositional differences between the forests impacted by the debris flows and the undisturbed reference forests. These differences can only be attributed to disturbance history. Unlike comparable cove forests in North Carolina, we did not find evidence of great laurel proliferation in disturbed or reference forests. Soil thickness varied spatially, with some sites recovering less than 2 cm of soil while others recovered soil at comparable depths to their reference site's soil pit depth. The drainage area that corresponds to a transition from predominantly colluvial erosion to fluvial erosion is several orders of magnitude smaller for the study site compared to topographically similar catchments in different climate and tectonic regimes, suggesting the importance of debris flows as a dominant erosional process for this landscape. These findings suggest that debris flows result in long-term changes to the soil and forest in this region, and that the properties of soil and vegetation may lead to slope failure at lower drainage areas than other studies predict. To improve forecasts for debris flow vulnerability in the region, we propose further study of controls by plant roots on the frequency or magnitude of debris flow events, and how that may change as climate change potentially accelerates ecological succession and decreases the return period for debris flow-triggering rainfall events.

Acknowledgments

This work was supported by the 4-VA Collaborative Grants Program and the H. G. Goodell Fund at the University of Virginia. I would like to acknowledge Carolyn Copenheaver, John Peterson, and Ethan Frye for contributions in the field, Roman DiBiase for helpful discussions, and Jean Lorber and Sam Truslow at the Nature Conservancy for advice and land access. I also thank Youwei Wang and Elise Heffernan for invaluable assistance with data analysis.

Open Research

Data from this study are at archived at Zenodo (Ackerman, 2025).

Tables

Table 1. Site naming conventions for vegetation and soil survey sites in Fortune's Cove, as well as physical characteristics of surveyed sites.

Hollow	Topographic position	Disturbance status	Hollow ID	Plot mean elevation (m)	Plot mean slope (°)	Aspect (°)
1	top	Disturbed	1Dtop	454	36	124
1	top	Reference	1Rtop	455	28	143
1	mid	Disturbed	1Dmid	380	23	158
1	mid	Reference	1Rmid	366	18	54
1	base	Disturbed	1Dbase	300	9	110
1	base	Reference	1Rbase	283	8	84
2	top	Disturbed	2Dtop	514	37	121
2	top	Reference	2Rtop	540	36	118
2	mid	Disturbed	2Dmid	413	22	126
2	mid	Reference	2Rmid	428	33	86
2	base	Disturbed	2Dbase	343	18	69
2	base	Reference	2Rbase	345	29	176
3	top	Disturbed	3Dtop	588	40	92
3	top	Reference	3Rtop	615	33	114
3	mid	Disturbed	3Dmid	451	22	121
3	mid	Reference	3Rmid	470	27	147
3	base	Disturbed	3Dbase	379	26	89
3	base	Reference	3Rbase	387	28	35

Table 2. Importance values for the top three species in the understory, midstory, and overstory at both debris flow sites and reference forest sites in Fortune's Cove.

i. Debris flow: Understory							
Species	**Frequency**	**Relative Frequency**	**Density (stems/ha)**	**Relative Density**	**Dominance (m^2/ha)**	**Relative Dominance**	**Importance Value**
Lindera benzoin	4	6.15	2951	19.19	-	-	12.67
Sassafras albidum	4	6.15	2396	15.58	-	-	10.86
Parthenocissus quinquefolia	6	9.23	1528	9.93	-	-	9.58
ii. Reference: Understory							
Species	**Frequency**	**Relative Frequency**	**Density (stems/ha)**	**Relative Density**	**Dominance (m^2/ha)**	**Relative Dominance**	**Importance Value**
Sassafras albidum	9	8.11	6042	17.70	-	-	12.91
Fraxinus pennsylvanica	7	6.31	3542	10.40	-	-	8.35
Cercis canadensis	6	5.41	3646	10.70	-	-	8.049
iii. Debris flow: Midstory							
Species	**Frequency**	**Relative Frequency**	**Density (tree/ha)**	**Relative Density**	**Dominance (m^2/ha)**	**Relative Dominance**	**Importance Value**
Betula lenta	4	12.90	208	11.45	0.39	42.56	22.30
Lindera benzoin	3	9.68	597	32.83	0.018	1.99	14.83
Acer rubrum	3	9.68	111	6.11	0.15	16.074	10.62
iv. Reference: Midstory							
Species	**Frequency**	**Relative Frequency**	**Density (tree/ha)**	**Relative Density**	**Dominance (m^2/ha)**	**Relative Dominance**	**Importance Value**
Sassafras albidum	5	11.11	653	28.31	0.81	26.46	21.96
Acer rubrum	7	15.56	264	11.45	0.43	13.98	13.66
snag	5	11.11	264	11.45	0.51	16.49	13.02
v. Debris flow: Overstory							
Species	**Frequency**	**Relative Frequency**	**Density (tree/ha)**	**Relative Density**	**Dominance (m^2/ha)**	**Relative Dominance**	**Importance Value**
Betula lenta	9	29.032	206	51.39	3.80	31.84	37.42
Liriodendron tulipifera	6	19.36	56	13.89	3.057	25.65	19.63
snag	7	22.58	56	13.89	1.14	9.55	15.34
vi. Reference: Overstory							
Species	**Frequency**	**Relative Frequency**	**Density (tree/ha)**	**Relative Density**	**Dominance (m^2/ha)**	**Relative Dominance**	**Importance Value**
Liriodendron tulipifera	8	15.39	200	33.67	21.89	52.85	33.97

snag	7	13.46	61	10.29	5.79	13.98	12.58
Sassafras albidum	7	13.46	100	16.84	1.98	4.79	11.69

Table 3. Coefficients from fitting equations 1 and 2 to the Nelson County sites compared with values from past studies in other climates.

Site (abbreviation)	S_0 [m/m]	a_1 [$1/m^{2a_2}$]	a_2	A_{cs} [m^2]	R^2 for fit
Fortune's Cove (FORT)	0.65	0.00913 $m^{-0.94}$	0.47	2.43 x 10^4	0.94
Davis Creek (DAV)	0.70	0.0643 $m^{-0.64}$	0.32	5.17 x 10^3	0.94
Freshwater Creek (FRESH)	0.78	0.0543 $m^{-0.66}$	0.33	7.06 x 10^3	0.93
Wills Cove (WILLS)	0.70	0.0421 $m^{-0.70}$	0.35	9.38 x 10^3	0.94
Snow Creek, northern San Jacinto Mountains[a]	0.76	0.67 $km^{-1.22}$	0.61	1.9 x 10^6	-
Cucamonga Creek, San Gabriel Mountains[a]	0.76	1.5 $km^{-1.06}$	0.53	5.0 x 10^5	-
San Gabriel mountains, 396887 m E 3799338 m N[b]	0.42	-	-	1.5 x 10^5	0.95
San Gabriel Mountains, 384971 m E 3799277 m N[b]	0.56	-	-	1.7 x 10^5	0.97
San Gabriel Mountains, 417896 m E 3792642 m N[b]	0.68	-	-	2.5 x10^5	0.97

[a]Neely & DiBiase (2023).
[b](McGuire et al., 2023)

Figures

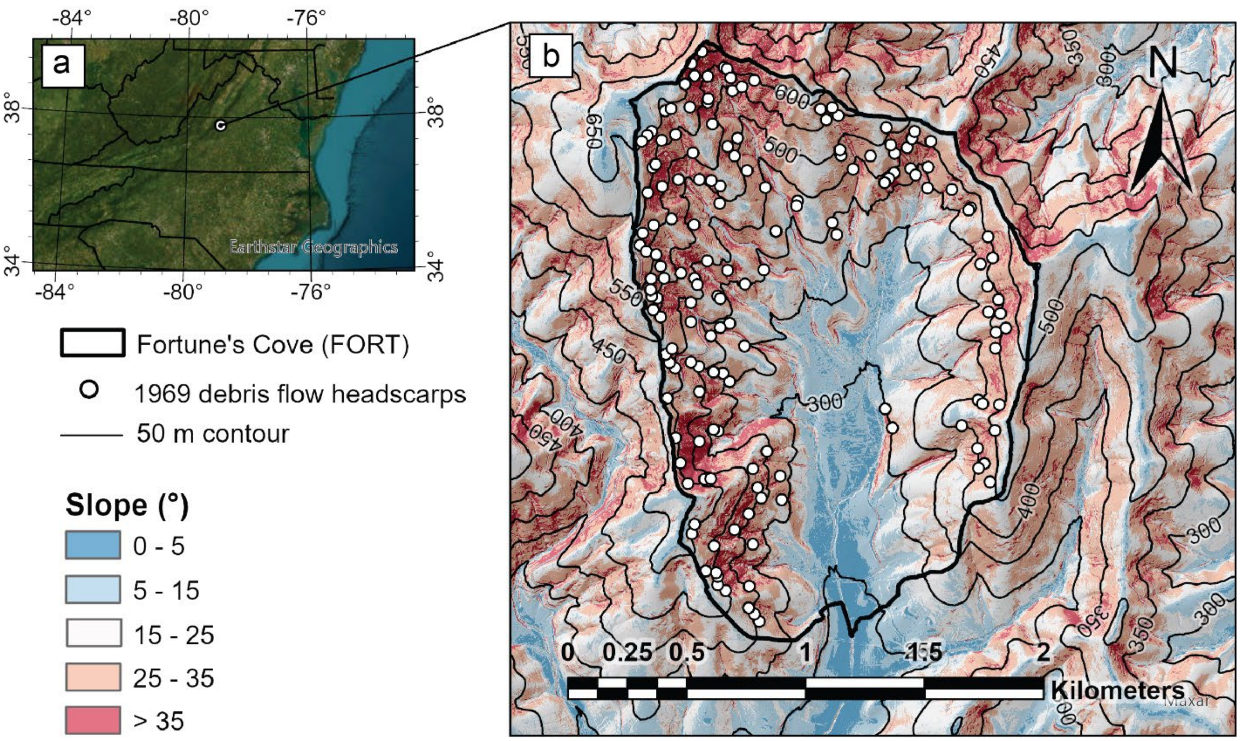

Figure 1. a) The location of the study area at Fortune's Cove (white circle) in central Virginia in the eastern United States. **b)** Map of topographic slope, including elevation contours (50-meter interval) and headscarps from 1969 debris flows (white circles).

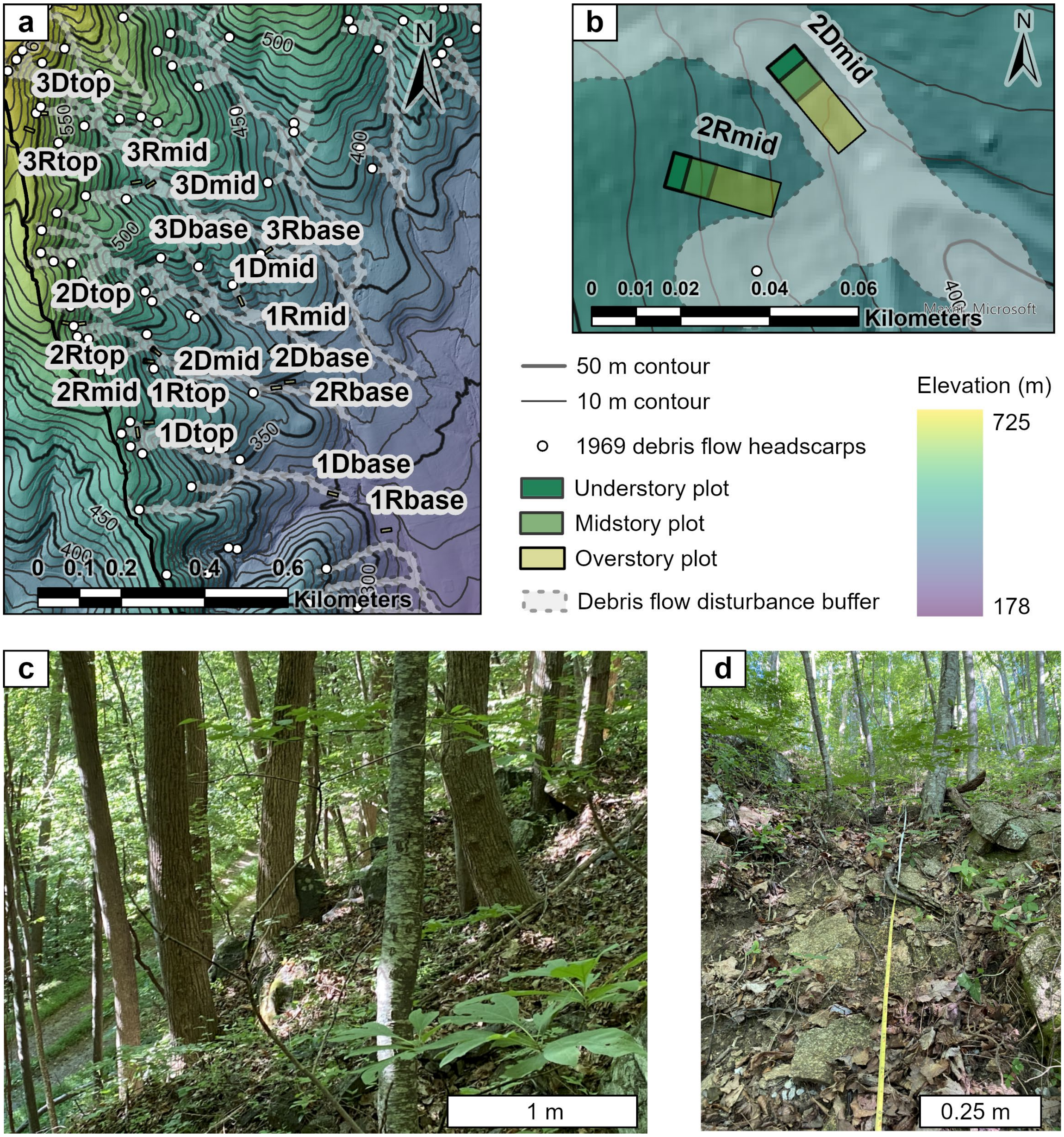

Figure 2. a) Sites for vegetation surveys and their locations relative to each other and to the debris flow disturbance buffer. Soil survey locations were outside the vegetation survey boundary, on the uphill side of plots, except when hazards prevented it. For naming conventions, see Table 1. **b)** The locations of the nested disturbed (2Dmid) and reference (2Rmid) nested vegetation survey plots for the 2D/Rmid site. **c)** Trees in the1Dtop plot and surrounding forest, with boulders caught on trees and pistol butt-shaped trunks. **d)** View looking up the plot at the 1Dtop site.

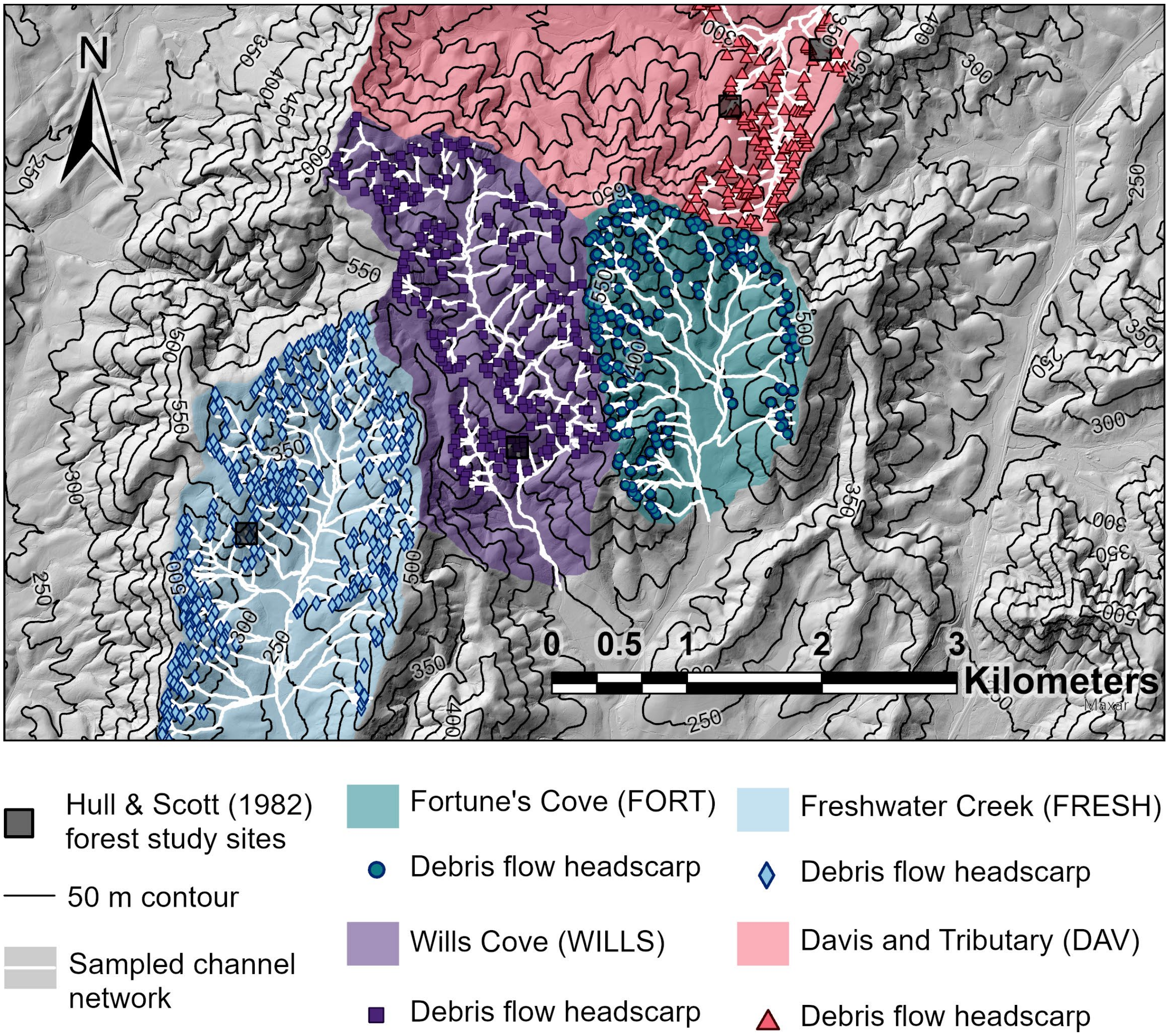

Figure 3. Watersheds and channel networks for Fortune's Cove and the four study sites from Hull and Scott (Hull & Scott, 1982): Davis Creek/Tributary, Freshwater Creek, and Wills Cove. These channel networks were used to calculate slope-drainage area relationships for each cove.

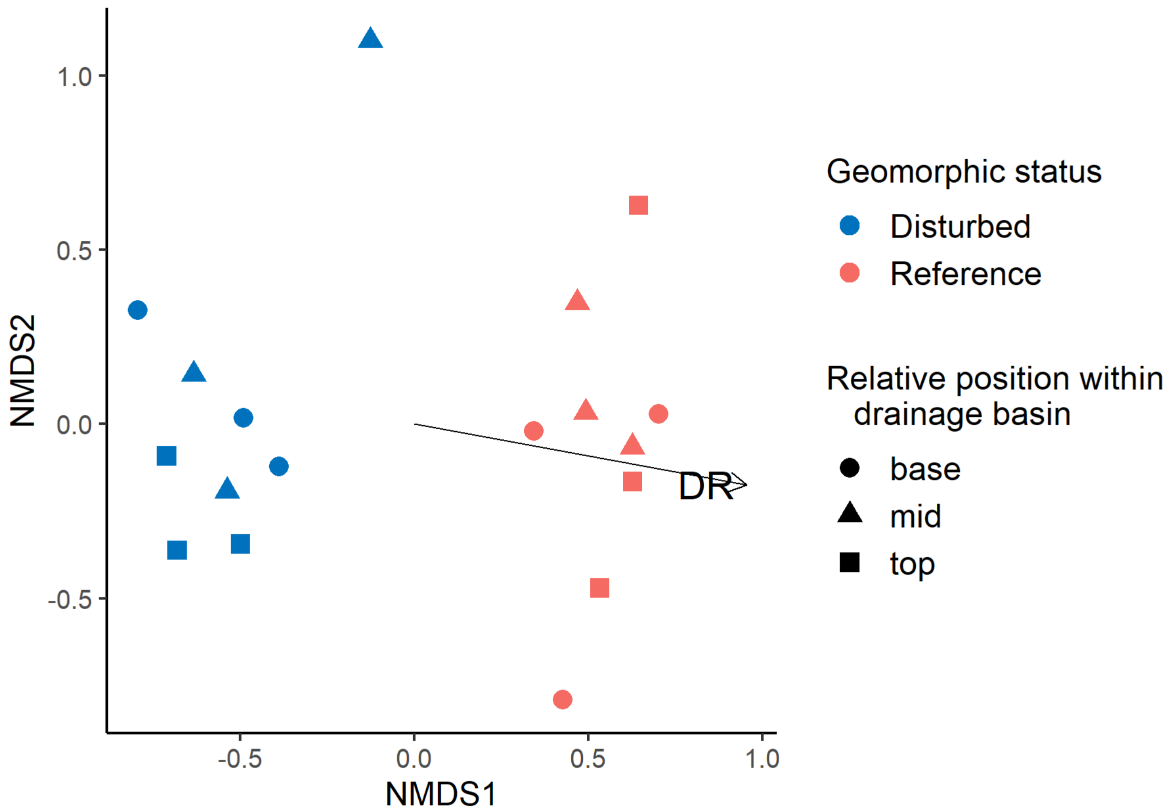

Figure 4. Non-metric multidimensional scaling (NMDS) plot for the overstory tree densities with minor species removed and genus-level categories combined. The closer together any points are in space, the more similar they are to each other. The arrow DR points in the direction of rapid change in an environmental variable — in this case, disturbance status (disturbed, D; or undisturbed reference, R), the strongest variable — and the length of the arrow shows strength of that gradient between communities in disturbed versus undisturbed forests.

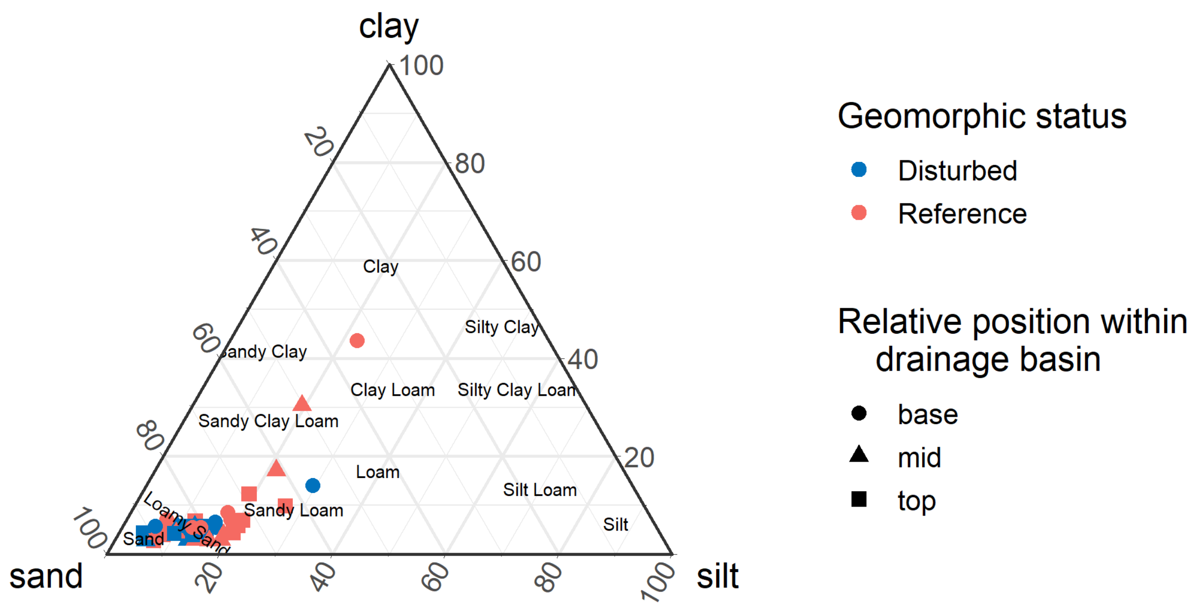

Figure 5. Ternary diagram for percent sand, clay and silt of all samples across all sites in Fortune's Cove.

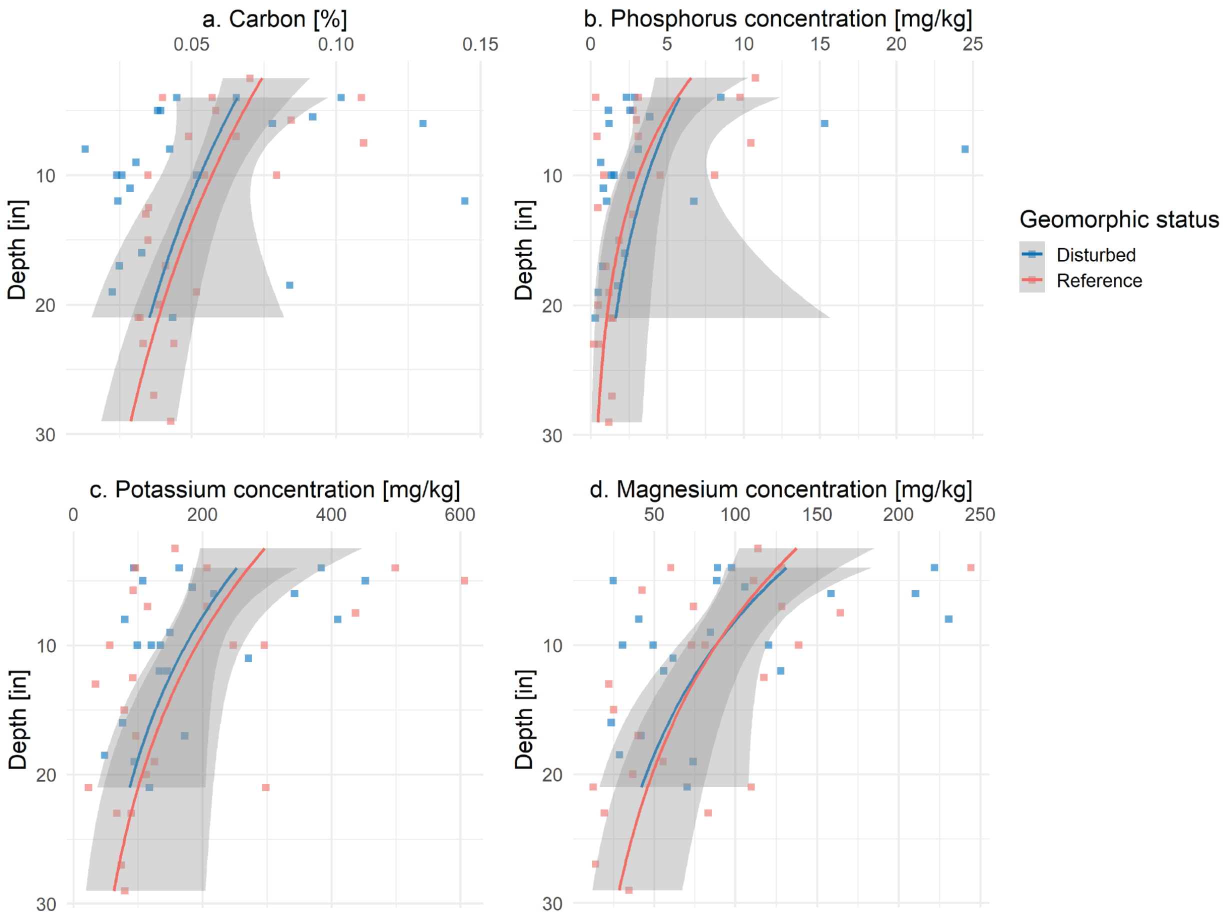

Figure 6. Elemental concentration versus depth for across all samples at all study sites, including **a)** percent carbon, **b)** phosphorous, **c)** potassium, and **d)** magnesium. Samples are distinguished between sites disturbed by debris flows (blue) and undisturbed reference sites (red).

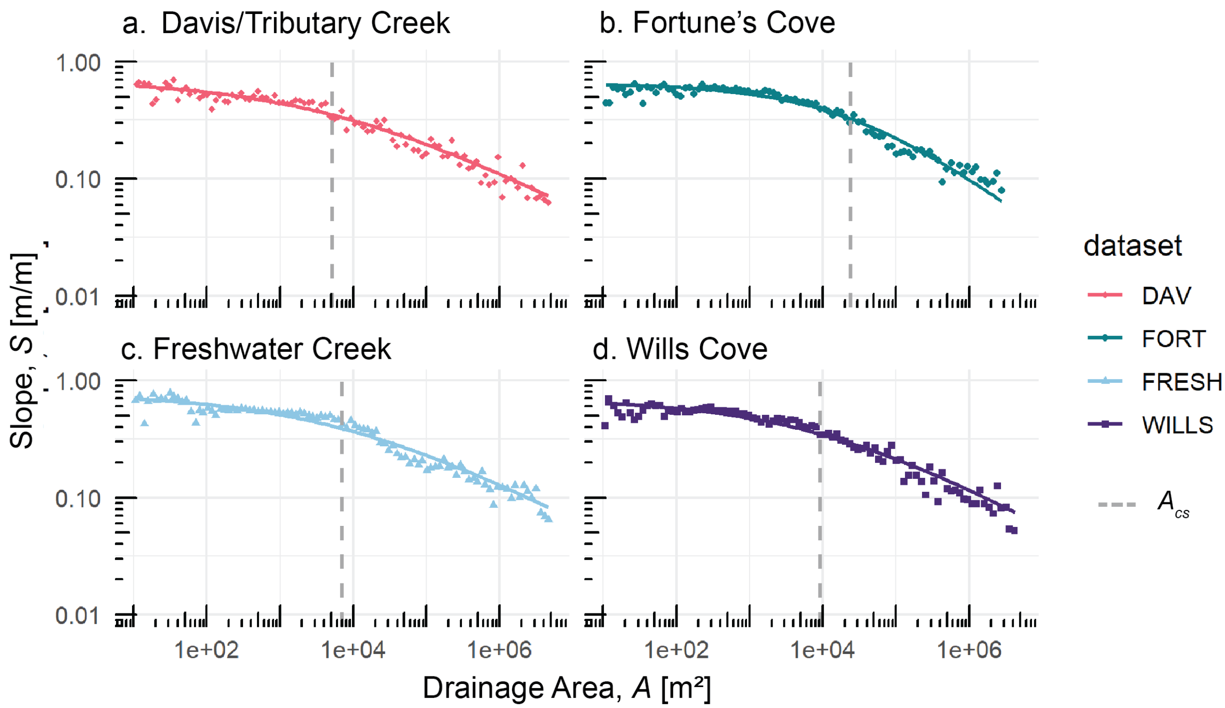

Figure 7. Plots of the mean slope (S) versus drainage area (A) sampled along channel networks at Fortune's Cove (FORT) and three nearby locations shown in Figure 3. Data are binned by drainage area (100 logarithmically spaced bins). Solid lines indicate the best fit using a nonlinear least squares regression for the binned data to the equation $S = S_0/(1+a_1*A\text{^}a_2)$, where S_0 is equal to the maximum binned mean slope for each cove. From the empirically derived coefficients a_1 and a_2, we derived A_{cs}, the transition between colluvial and fluvial processes. A_{cs} for each cove is marked with a grey dashed line.

References

Abrams, M. D., & Nowacki, G. J. (1992). Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania. *Bulletin of the Torrey Botanical Club*, *119*(1), 19–28. https://doi.org/10.2307/2996916

Ackerman, A. (2025). Supporting Data for Effects of Landslide Disturbance on Soil and Vegetation in a Steep Landscape in Central Virginia (Version 1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15305176

Alexander, H. D., Siegert, C., Brewer, J. S., Kreye, J., Lashley, M. A., McDaniel, J. K., et al. (2021). Mesophication of oak landscapes: Evidence, knowledge gaps, and future research. *BioScience*, *71*(5), 531–542. https://doi.org/10.1093/biosci/biaa169

Arundel, S. T., Archuleta, C.-A. M., Phillips, L. A., Roche, B. L., & Constance, E. W. (2015). *1-Meter Digital Elevation Model specification* (No. 11-B7). *Techniques and Methods*. U.S. Geological Survey. https://doi.org/10.3133/tm11B7

Balaguru, K., Xu, W., Chang, C.-C., Leung, L. R., Judi, D. R., Hagos, S. M., et al. (2023). Increased U.S. coastal hurricane risk under climate change. *Science Advances*, *9*(14), eadf0259. https://doi.org/10.1126/sciadv.adf0259

Band, L. E., Hwang, T., Hales, T. C., Vose, J., & Ford, C. (2012). Ecosystem processes at the watershed scale: mapping and modeling ecohydrological controls. *Geomorphology 137(1):159-167*, *137*, 159–167. https://doi.org/10.1016/j.geomorph.2011.06.025

van Breugel, M., Bongers, F., Norden, N., Meave, J. A., Amissah, L., Chanthorn, W., et al. (2024). Feedback loops drive ecological succession: towards a unified conceptual framework. *Biological Reviews*, *99*(3), 928–949. https://doi.org/10.1111/brv.13051

Brose, P. H. (2016). Origin, development, and impact of mountain laurel thickets on the mixed-oak forests of the central Appalachian Mountains, USA. *Forest Ecology and Management*, *374*, 33–41. https://doi.org/10.1016/j.foreco.2016.04.040

Brose, P. H., Schuler, T., Lear, D. V., & Berst, J. (2001). Bringing fire back: The changing regimes of the Appalachian mixed-oak forest. *Journal of Forestry. 99(11): 30-35.*, *99*, 30–35.

Burns, R. M., & Honkala, B. H. (Eds.). (1990). *Silvics of North America* (Vol. 2-Hardwoods). Washington, D.C.: U.S. Department of Agriculture Forest Service. Retrieved from https://www.srs.fs.usda.gov/pubs/misc/ag_654/table_of_contents.htm

Cannon, S. H., Boldt, E. M., Laber, J. L., Kean, J. W., & Staley, D. M. (2011). Rainfall intensity–duration thresholds for postfire debris-flow emergency-response planning. *Natural Hazards*, *59*(1), 209–236. https://doi.org/10.1007/s11069-011-9747-2

Carter-Witt, A., & Whitehead, D. (2019). The 50th anniversary of Hurricane Camille in Nelson County: New insights into landslides, meteorology, and geology. Presented at the 49th Virginia Geological Field Conference.

Cenderelli, D. A., & Kite, J. S. (1998). Geomorphic effects of large debris flows on channel morphology at North Fork Mountain, eastern West Virginia, USA. *Earth Surface Processes and Landforms*, *23*(1), 1–19. https://doi.org/10.1002/(SICI)1096-9837(199801)23:1<1::AID-ESP814>3.0.CO;2-3

Coussot, P., & Meunier, M. (1996). Recognition, classification and mechanical description of debris flows. *Earth-Science Reviews*, *40*(3–4), 209–227. https://doi.org/10.1016/0012-8252(95)00065-8

Cui, W., Chen, J., Chen, X., Song, D., Zhao, W., & Jin, K. (2024). Effect of topographic slope on the interaction between debris flows and riparian forests. *Landslides*, *21*(4), 889–900. https://doi.org/10.1007/s10346-023-02183-8

Deljouei, A., Cislaghi, A., Abdi, E., Borz, S. A., Majnounian, B., & Hales, T. C. (2023). Implications of hornbeam and beech root systems on slope stability: from field and laboratory measurements to modelling methods. *Plant and Soil*, *483*(1), 547–572. https://doi.org/10.1007/s11104-022-05764-z

Desta, F., Colbert, J. J., Rentch, J. S., & Gottschalk, K. W. (2004). Aspect induced differences in vegetation, soil, and microclimatic characteristics of an Appalachian watershed. *Castanea*, *69*(2), 92–108. https://doi.org/10.2179/0008-7475(2004)069<0092:AIDIVS>2.0.CO;2

Dudley, M. P., Freeman, M., Wenger, S., Jackson, C. R., & Pringle, C. M. (2020). Rethinking foundation species in a changing world: The case for *Rhododendron maximum* as an *emerging* foundation species in shifting ecosystems of the southern Appalachians. *Forest Ecology and Management*, *472*, 118240. https://doi.org/10.1016/j.foreco.2020.118240

Eaton, L. S., Morgan, B. A., Craig Kochel, R., & Howard, A. D. (2003). Quaternary deposits and landscape evolution of the central Blue Ridge of Virginia. *Geomorphology*, *56*(1–2), 139–154. https://doi.org/10.1016/S0169-555X(03)00075-8

Eaton, L. S., Morgan, B. A., Kochel, R. C., & Howard, A. D. (2003). Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia. *Geology*, *31*(4), 339–342. https://doi.org/10.1130/0091-7613(2003)031<0339:RODFIL>2.0.CO;2

Elliott, K. J., & Hewitt, D. (1997). Forest species diversity in upper elevation hardwood forests in the southern Appalachian mountains. *Castanea*, *62*(1), 32–42. https://www.jstor.org/stable/4034101

Evans, N. H. (1991). Latest Precambrian to Ordovician metamorphism in the Virginia Blue Ridge; origin of the contrasting Lovingston and Pedlar basement terranes. *American Journal of Science*, *291*(5), 425–452. https://doi.org/10.2475/ajs.291.5.425

Ford, C. R., Elliott, K. J., Clinton, B. D., Kloeppel, B. D., & Vose, J. M. (2012a). Forest dynamics following eastern hemlock mortality in the southern Appalachians. *Oikos*, *121*(4), 523–536. https://doi.org/10.1111/j.1600-0706.2011.19622.x

Ford, C. R., Elliott, K. J., Clinton, B. D., Kloeppel, B. D., & Vose, J. M. (2012b). Forest dynamics following eastern hemlock mortality in the southern Appalachians. *Oikos*, *121*(4), 523–536. https://doi.org/10.1111/j.1600-0706.2011.19622.x

Freund, C. A., Clark, K. E., Curran, J. F., Asner, G. P., & Silman, M. R. (2021). Landslide age, elevation and residual vegetation determine tropical montane forest canopy recovery and biomass accumulation after landslide disturbances in the Peruvian Andes. *Journal of Ecology*, *109*(10), 3555–3571. https://doi.org/10.1111/1365-2745.13737

Gabet, E. J., & Dunne, T. (2002). Landslides on coastal sage-scrub and grassland hillslopes in a severe El Niño winter: The effects of vegetation conversion on sediment delivery. *GSA Bulletin*, *114*(8), 983–990. https://doi.org/10.1130/0016-7606(2002)114<0983:LOCSSA>2.0.CO;2

Hack, J. T., & Goodlett, J. C. (1960). *Geomorphology and forest ecology of a mountain region in the central Appalachians* (Report No. 347) (p. 77). U.S. Geological Survey.

Hales, T. C. (2018). Modelling biome-scale root reinforcement and slope stability. *Earth Surface Processes and Landforms*, *43*(10), 2157–2166. https://doi.org/10.1002/esp.4381

Hales, T. C., & Miniat, C. F. (2017). Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability. *Earth Surface Processes and Landforms*, *42*(5), 803–813. https://doi.org/10.1002/esp.4039

Hales, T. C., Ford, C. R., Hwang, T., Vose, J. M., & Band, L. E. (2009). Topographic and ecologic controls on root reinforcement. *Journal of Geophysical Research: Earth Surface*, *114*(F3). https://doi.org/10.1029/2008JF001168

Haugo, R. D., Halpern, C. B., & Bakker, J. D. (2011). Landscape context and long-term tree influences shape the dynamics of forest-meadow ecotones in mountain ecosystems. *Ecosphere*, *2*(8), art91. https://doi.org/10.1890/ES11-00110.1

Hull, J. C., & Scott, R. C. (1982). Plant Succession on debris avalanches of Nelson County, Virginia. *Castanea*, *47*(2), 158–176.

Hwang, T., Band, L. E., Hales, T. C., Miniat, C. F., Vose, J. M., Bolstad, P. V., et al. (2015). Simulating vegetation controls on hurricane-induced shallow landslides with a distributed ecohydrological model. *Journal of Geophysical Research: Biogeosciences*, *120*(2), 361–378. https://doi.org/10.1002/2014JG002824

Imaizumi, F., Sidle, R. C., Tsuchiya, S., & Ohsaka, O. (2006). Hydrogeomorphic processes in a steep debris flow initiation zone. *Geophysical Research Letters*, *33*(10). https://doi.org/10.1029/2006GL026250

Iverson, R. M. (1997). The physics of debris flows. *Reviews of Geophysics*, *35*(3), 245–296. https://doi.org/10.1029/97RG00426

Iverson, R. M. (2000). Landslide triggering by rain infiltration. *Water Resources Research*, *36*(7), 1897–1910. https://doi.org/10.1029/2000WR900090

Iverson, R. M., Reid, M. E., & LaHusen, R. G. (1997). Debris-Flow Mobilization from Landslides. *Annual Review of Earth and Planetary Sciences*, *25*(1), 85–138. https://doi.org/10.1146/annurev.earth.25.1.85

Jakob, M., Bovis, M., & Oden, M. (2005). The significance of channel recharge rates for estimating debris-flow magnitude and frequency. *Earth Surface Processes and Landforms*, *30*(6), 755–766. https://doi.org/10.1002/esp.1188

Kean, J. W., McCoy, S. W., Tucker, G. E., Staley, D. M., & Coe, J. A. (2013). Runoff-generated debris flows: Observations and modeling of surge initiation, magnitude, and frequency. *Journal of Geophysical Research: Earth Surface*, *118*(4), 2190–2207. https://doi.org/10.1002/jgrf.20148

Lafon, C. W., Naito, A. T., Grissino-Mayer, H. D., Horn, S. P., & Waldrop, T. A. (2017). *Fire history of the Appalachian region: a review and synthesis* (No. SRS-GTR-219) (p. SRS-GTR-219). Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. https://doi.org/10.2737/SRS-GTR-219

Libohova, Z., Seybold, C., Wysocki, D., Wills, S., Schoeneberger, P., Williams, C., et al. (2018). Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey Characterization Database. *Journal of Soil and Water Conservation*, *73*(4), 411–421. https://doi.org/10.2489/jswc.73.4.411

Lv, M., Xu, Z., Yang, Z.-L., Lu, H., & Lv, M. (2021). A comprehensive review of specific yield in land surface and groundwater studies. *Journal of Advances in Modeling Earth Systems*, *13*(2), e2020MS002270. https://doi.org/10.1029/2020MS002270

McCune, B., & Grace, J. B. (2002). Nonmetric Multidimensional Scaling. In *Analysis of Ecological Communities* (pp. 125–142). Gleneden Beach, Oregon: MjM Software Design.

McGuire, L. A., McCoy, S. W., Marc, O., Struble, W., & Barnhart, K. R. (2023). Steady-state forms of channel profiles shaped by debris-flow and fluvial processes. *Earth Surface Dynamics*, *11*(6), 117–1143. https://doi.org/10.5194/esurf-11-1117-2023

Mirus, B. B., Staley, D. M., Kean, J. W., Smith, J. B., Wooten, R., McGuire, L. A., & Ebel, B. A. (2019). Conceptual framework for assessing disturbance impacts on debris- flow initiation thresholds across hydroclimatic settings.

Montgomery, D. R., & Dietrich, W. E. (1988). Where do channels begin? *Nature*, *336*, 232–234. https://doi.org/10.1038/336232a0

Montgomery, D. R., Schmidt, K. M., Dietrich, W. E., & McKean, J. (2009). Instrumental record of debris flow initiation during natural rainfall: Implications for modeling slope stability. *Journal of Geophysical Research: Earth Surface*, *114*(F1). https://doi.org/10.1029/2008JF001078

Neely, A. B., & DiBiase, R. A. (2023). Sediment controls on the transition from debris flow to fluvialchannels in steep mountain ranges. *Earth Surface Processes and Landforms*, *48*(7), 1305–1483. https://doi.org/10.1002/esp.5553

Nieto Ferreira, R., Nissenbaum, M. R., & Rickenbach, T. M. (2018). Climate change effects on summertime precipitation organization in the Southeast United States. *Atmospheric Research*, *214*, 348–363. https://doi.org/10.1016/j.atmosres.2018.08.012

Osterkamp, W. R., Hupp, C. R., & Schening, M. R. (1995). Little River revisited — thirty-five years after Hack and Goodlett. *Geomorphology*, *13*(1), 1–20. https://doi.org/10.1016/0169-555X(95)00063-B

Paillet, F. L. (2002). Chestnut: history and ecology of a transformed species. *Journal of Biogeography*, *29*(10–11), 1517–1530. https://doi.org/10.1046/j.1365-2699.2002.00767.x

Parker, R. N., Hales, T. C., Mudd, S. M., Grieve, S. W. D., & Constantine, J. A. (2016). Colluvium supply in humid regions limits the frequency of storm-triggered landslides. *Scientific Reports*, *6*(1), 34438. https://doi.org/10.1038/srep34438

Piciullo, L., Calvello, M., & Cepeda, J. M. (2018). Territorial early warning systems for rainfall-induced landslides. *Earth-Science Reviews*, *179*, 228–247. https://doi.org/10.1016/j.earscirev.2018.02.013

Prach, K., & Walker, L. R. (2019). Differences between primary and secondary plant succession among biomes of the world. *Journal of Ecology*, *107*(2), 510–516. https://doi.org/10.1111/1365-2745.13078

Ramos Scharrón, C. E., Castellanos, E. J., & Restrepo, C. (2012). The transfer of modern organic carbon by landslide activity in tropical montane ecosystems. *Journal of Geophysical Research: Biogeosciences*, *117*(G3). https://doi.org/10.1029/2011JG001838

Restrepo, C., Vitousek, P., & Neville, P. (2003). Landslides significantly alter land cover and the distribution of biomass: an example from the Ninole ridges of Hawai'i. *Plant Ecology, 166*(1), 131–143. https://doi.org/10.1023/A:1023225419111

Restrepo, C., Walker, L. R., Shiels, A. B., Bussmann, R., Claessens, L., Fisch, S., et al. (2009). Landsliding and its multiscale influence on mountainscapes. *BioScience*, *59*(8), 685–698. https://doi.org/10.1525/bio.2009.59.8.10

Rice, A., Perdrial, N., Treto, V., D'Amato, A., Smith, G., & Richardson, J. (2024). Influence of parent material mineralogy on forest soil nutrient release rates across a nutrient richness gradient. *Geoderma*, *451*. https://doi.org/10.1016/j.geoderma.2024.117081

Roering, J. J., Perron, J. T., & Kirchner, J. W. (2007). Functional relationships between denudation and hillslope form and relief. *Earth and Planetary Science Letters*, *264*(1), 245–258. https://doi.org/10.1016/j.epsl.2007.09.035

Schomakers, J., Jien, S.-H., Lee, T.-Y., Huang, J.-C., Hseu, Z.-Y., Lin, Z. L., et al. (2017). Soil and biomass carbon re-accumulation after landslide disturbances. *Geomorphology*, *288*, 164–174. https://doi.org/10.1016/j.geomorph.2017.03.032

Sidle, R. C., & Bogaard, T. A. (2016). Dynamic earth system and ecological controls of rainfall-initiated landslides. *Earth-Science Reviews*, *159*, 275–291. https://doi.org/10.1016/j.earscirev.2016.05.013

Smith, J. A., Baeck, M. L., Ntelekos, A. A., Villarini, G., & Steiner, M. (2011). Extreme rainfall and flooding from orographic thunderstorms in the central Appalachians. *Water Resources Research*, *47*(4). https://doi.org/10.1029/2010WR010190

Stephenson, S., & Mills, H. (1999). Contrasting vegetation of noses and hollows in the Valley and Ridge Province, Southwestern Virginia. *The Journal of the Torrey Botanical Society*, *126*(3), 197–212. https://doi.org/10.2307/2997275

Stock, J. D., & Dietrich, W. E. (2003). Valley incision by debris flows: Evidence of a topographic signature. *Water Resources Research*, *39*(4). https://doi.org/10.1029/2001WR001057

Stock, J. D., & Dietrich, W. E. (2006). Erosion of steepland valleys by debris flows. *Geological Society of America Bulletin*, *118*(9–10), 1125–1148. https://doi.org/10.1130/B25902.1

Stoffel, M., Allen, S. K., Ballesteros-Cánovas, J. A., Jakob, M., & Oakley, N. (2024). Climate Change Effects on Debris Flows. In M. Jakob, S. McDougall, & P. Santi (Eds.), *Advances in Debris-flow Science and Practice* (1st ed., pp. 273–308). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-48691-3_10

Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1991). On the extraction of channel networks from digital elevation data. *Hydrological Processes*, *5*(1), 81–100. https://doi.org/10.1002/hyp.3360050107

U.S. Geological Survey. (2015). 3D Elevation Program 1-Meter Resolution Digital Elevation Model (Version 20200330) [Data set]. Retrieved from https://www.sciencebase.gov/catalog/item/5ead05bd82cefae35a253b3e

Van Lear, D. H., Vandermast, D. B., Rivers, C. T., Baker, T. T., Hedman, C. W., Clinton, B. D., & Waldrop, T. A. (2002). American chestnut, rhododendron, and the future of Appalachian cove forests. In *Proceedings of the eleventh biennial southern silvicultural research conference* (p. 622). Asheville, NC: Department of Agriculture, Forest Service, Southern Research Station.

Vandermast, D. B., & Van Lear, D. H. (2002). Riparian vegetation in the southern Appalachian mountains (USA) following chestnut blight. *Forest Ecology and Management*, *155*(1), 97–106. https://doi.org/10.1016/S0378-1127(01)00550-3

Walker, L. R., & del Moral, R. (2003). *Primary succession and ecosystem rehabilitation*. Cambridge, UK ; New York: Cambridge University Press.

Walker, L. R., & Shiels, A. B. (2013). *Landslide Ecology*. Cambridge University Press. Retrieved from https://digitalcommons.unl.edu/icwdm_usdanwrc/1644

Walker, L. R., Velázquez, E., & Shiels, A. B. (2009). Applying lessons from ecological succession to the restoration of landslides. *Plant and Soil*, *324*(1), 157–168. https://doi.org/10.1007/s11104-008-9864-1

Wang, S., Zhao, M., Meng, X., Chen, G., Zeng, R., Yang, Q., et al. (2020). Evaluation of the effects of forest on slope stability and its implications for forest management: A case study of Bailong River basin, China. *Sustainability*, *12*(16), 6655. https://doi.org/10.3390/su12166655

Whipple, K. X. (2009). The influence of climate on the tectonic evolution of mountain belts. *Nature Geoscience*, *2*(2), 97–104. https://doi.org/10.1038/ngeo413

Whipple, K. X., & Dunne, T. (1992). The influence of debris-flow rheology on fan morphology, Owens Valley, California. *Geological Society of America Bulletin*, *104*(7), 887–900. https://doi.org/10.1130/0016-7606(1992)104<0887:TIODFR>2.3.CO;2

Whittecar, G. R., & Ryter, D. W. (1992). Boulder streams, debris fans, and pleistocene climate change in the Blue Ridge Mountains of Central Virginia. *The Journal of Geology*, *100*(4), 487–494. https://doi.org/10.1086/629600

Williams, G., & Guy, H. (1973). *Erosional and depositional aspects of Hurricane Camille in Virginia, 1969* (Professional Paper No. 804) (p. 80). U.S. Geological Survey.

Wooten, R. M., Witt, A. C., Miniat, C. F., Hales, T. C., & Aldred, J. L. (2016). Frequency and magnitude of selected historical landslide events in the southern Appalachian Highlands of North Carolina and Virginia: Relationships to rainfall, geological and ecohydrological controls, and effects. In C. H. Greenberg & B. S. Collins (Eds.), *Natural disturbances and historic range of variation: Type, frequency, severity, and post-disturbance structure in central hardwood forests USA* (pp. 203–262). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-21527-3_9