2022

Examining the Effect of Public Hiking Trail Use on Soil Loss and Stream-Bottom Embeddedness in First-Order Vermont Streams

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Undergraduate senior thesis conducted as part of requirements for the Environmental Science Bachelor of Science degree through the Rubenstein School of the Environment and Natural Resources and the Honors College

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Abstract

Erosion of public hiking trails is a key management issue in Vermont. Previous studies have suggested a link between outdoor recreational land use, soil erosion, and diminished stream health. Trail development, maintenance, and use in Vermont is regulated through a series of state and local regulations. This study investigated the relationship between hiking trail character (trail age, visitation rate, and trail-stream crossings) and soil loss on trails and the relationship between soil loss, stream-bottom embeddedness, and stream health. Nine paired trail-stream sites and one undeveloped forested stream site (control) were monitored to determine stream-bottom embeddedness, macroinvertebrate community composition, and soil incision on trails. Regression analysis was performed to determine the relationships present between trail characteristics, soil loss, and embeddedness. The results did not indicate any significant relationships between trail character, soil loss, and embeddedness. Stream-bottom embeddedness was significantly negatively related to stream gradient, indicating that natural geography has more impact than recreational land use on sediment dynamics in forested streams. None of the stream sites were impaired, as indicated by macroinvertebrate community composition. The results of this study may suggest that current trail regulations are effective in minimizing the impact of public hiking trail construction and use on trail-adjacent streams. Future work could focus on monitoring trails throughout their lifespan to better understand the long-term effects of trail use on the surrounding landscape. Future studies could also examine which methods are most effective in measuring soil loss on hiking trails and sediment dynamics in headwater streams.

Acknowledgements

I would like to thank Kris Stepenuck for her guidance throughout the research process. I would also like to express my gratitude to Mindy Morales-Williams and Walter Poleman for their contributions as part of my thesis committee. I was able to conduct this research thanks to funding through the Sustainability Award from the UVM Office of Fellowships, Opportunities, and Undergraduate Research (FOUR). Thank you to Keegan Tierney at the Green Mountain Club, who helped to shape the focus of my research, and to all the trail organizations who supported this study: Green Mountain Club, Catamount Trail Organization, Vermont State Parks, Blueberry Hill Outdoor Center, Green Mountain Audubon Center, and the Green Mountain National Forest. Lastly, thank you to all the friends and family who hiked with me and tolerated frequent water quality monitoring stops along the way.

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1. Introduction

1.1 Overview & Importance

Soil erosion from hiking trails is a key management issue for trail organizations in Vermont, particularly with steep trails and “mud season” conditions (K. Tierney, personal communication, February 2, 2021). Previous studies have indicated a relationship between trail erosion, soil loss, and increased sediment in trail-adjacent streams (Johnson et al., 2013; Olive & Marion, 2009). The focus of this study is to further understand how hiking trail use impacts soil erosion and stream sediment dynamics on hiking trails in Vermont.

1.2 Literature Review

1.2.1 Sediment and Stream Health

Sediment dynamics are a key element of stream health. Sedimentation rates are increasing globally due to changes in land cover, land use, and management practices. It is expected that fine sediment concentrations will continue to increase due to climate-driven increases in rainfall and runoff levels. Natural processes of fine sediment transport support healthy stream functioning. Human intervention, however, has led to sediment yields that exceed background levels and contribute to ecological degradation (Mathers et al., 2017).

Increased sediment loading is linked to changes in macroinvertebrate communities (Berry & Hill, 2003; Salmaso et al., 2020; Wood, 1997). Elevated levels of bedded and suspended sediment impact pelagic and benthic macroinvertebrates both directly, through abrasion, clogging of filtration mechanisms, and smothering, and indirectly, through the reduction of light availability and its impact on feeding behaviors (Berry & Hill, 2003). Sediment loading associated with mining operations has been correlated with biological impairment (Bona et al., 2016). Increased levels of fine sediment are associated with a reduction in coarse particulate organic matter (CPOM) because thick layers of sediment reduced the ability of the stream bottom to catch and retain coarse particles. A correlating decrease in the abundance of shredders, benthic macroinvertebrates that feed on CPOM has also been observed (Doretto et al., 2016). Macroinvertebrate communities were found to be lower in density, richness, and diversity directly following a rock-slope failure sedimentation event, with recovery of some sensitive taxa taking over a year (Salmaso et al., 2020).

Fine sediment levels have been found to be negatively related to dissolved oxygen levels, likely due to the decomposition of sediment-bound organic matter (Mathers et al., 2017). Increases in stream-bottom sediment and reduction of dissolved oxygen levels can decrease the viability of fish embryos and redds, particularly in salmonids. Fine sediment fills in gravel and cobble stream bottom habitat where fish lay their eggs, reducing water flow, limiting intra-gravel dissolved oxygen concentrations, and trapping fish larvae (Berry & Hill, 2003; Yamada & Nakamura, 2009). In addition, fine sediment may cause an overall reduction in prey availability for salmonids due to its negative impact on macroinvertebrate communities (Cover et al., 2008).

1.2.2 Natural Drivers of Stream Sediment Dynamics

Many different natural processes influence sediment concentration and transport in streams. Sediment flux is linked to stream flow, particularly during storm events. Stream discharge was found to be the main driver for sediment and organic matter fluxes in intermittent rivers and ephemeral streams in a subtropical watershed in Mississippi (Dewey et al., 2020). Most suspended sediment transport has been found to occur during flood events, including summer flash floods and snowmelt-induced mud flow events (Lenzi et al., 2003). Snowmelt is particularly important in headwater streams; a study of seasonal dynamics and exports from a first-order stream in Michigan found that snow melt is a dominant hydrological event in first-order streams, causing peak stream flows (Hofmeister et al., 2019).

Natural sediment regimes in rivers are determined by the climate and geology of their watershed, as well as upstream, lateral, and downstream inputs and outputs (Wohl et al., 2015). Hillslope erosion is a main source of suspended sediment in streams, according to an analysis of suspended sediments during flood events in a small, high-gradient stream (Lenzi & Marchi, 2000). In small, forested streams, channel morphology can be influenced by woody debris (Hassan et al., 2005).

1.2.3 Recreation Ecology

Recreation ecology describes the subset of studies that examine the relationship between recreational land use and its impacts on hydrology, vegetation, and wildlife. Many recreation ecology studies describe the curvilinear use-impact relationship; there is proportionally more ecological impact from initial recreational land use, then the relationship between use and impact becomes more linear over time. Several studies have also examined the relationship between recreational land use and response functions from plant communities, wildlife, soils, and aquatic systems. These responses tend to be more variable and localized. In aquatic systems, direct physical disturbance from recreational uses is associated with sedimentation, nutrient influx, and introduction of pathogens (Monz et al., 2013). The current study examines the impacts of direct and indirect physical disturbance from hiking trails on forested headwater streams in Vermont.

1.2.4 Impact of Public Hiking Trail Use

Several studies of hiking and multi-use public trails throughout the United States show that trail design and character, including trail grade, slope alignment angle, drainage features, position, and type of use, influence the levels of soil loss (Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009). Total suspended solids concentrations following storm events were found to be higher in a watershed containing off-highway vehicle trails than that of an undisturbed watershed, particularly during time periods when the trails were open and in use (Miniat et al., 2019). Another study at Mammoth Cave National Park in Kentucky conducted a biological integrity assessment of aquatic macroinvertebrates in the stream sections that run through the park's trail network. A biological integrity assessment of aquatic macroinvertebrates generally indicated excellent water quality for trail-adjacent streams, but a correlation was found between a major runoff impact area with significant visible soil loss and impaired biological integrity in that segment of the stream (Johnson et al., 2013). These results demonstrate that the impact of trail design and use for soil loss and stream health is widely variable and can be difficult to characterize.

Public hiking trails are an important form of land use in Vermont. The Vermont Outdoor Recreation Economy Report stated that 72 percent of Vermont residents participate in outdoor recreation every year, in addition to out-of-state tourists who travel to Vermont for outdoor recreation (*Vermont*, 2017). The outdoor sector is a significant driver of Vermont economy. Outdoor recreation has remained as a key economic sector through the onset of the COVID-19 pandemic. Despite the limitations that the COVID pandemic created, some evidence suggests that it increased outdoor recreation; in 2020, the Vermont State Park system saw its highest visitation rate since 1988 (Ault & Dagger, 2021). Given the economic and cultural importance of hiking in Vermont, it is important to examine the impact of public hiking trail use on soil loss and stream health.

According to the Green Mountain Club, soil erosion is a key management concern and has been the focus of many recent trail improvement projects (K. Tierney, personal communication, February 2, 2021). Soil erosion is of particular concern on Vermont trails for two main reasons. Firstly, Vermont has an extended “mud season” in the early spring, when trails are particularly vulnerable to water-driven erosion (McLane, 2021). Secondly, many sections of the Vermont Long Trail (the longest continuous trail in Vermont) are relatively steep. Steeper slopes are generally associated with greater soil loss by erosion (Assouline & Ben-Hur, 2006). The combination of steep, often muddy trail conditions and frequent trail use makes soil erosion an important research and management focus area in Vermont.

1.2.5 Sustainable Trail Development

Trail character, as discussed in the current study, encompasses how a trail is designed, constructed, used, and maintained. One of the most studied and regulated elements of trail character is trail development, which includes design and construction. The U.S. Forest Service defines five main considerations for trail development and management: trail type, trail class, managed use, designed use, and trail design parameters. Trail type describes the trail surface and type of recreational use (e.g. hiking, biking, cross-country skiing), and trail class describes the scale of development. Managed use is the type of recreational use for which a trail is actively managed. There can be several managed uses for a single trail or trail network. The designed use identifies the managed use that will require the most considerations for design, construction, and maintenance. Lastly, the trail design parameters provide technical guidelines for trail development. These parameters include tread width, surface, grade, cross slope, clearing, and turns (USFS, 2016). The Vermont Town Forest Trail Design Guide provides a framework for developing sustainable trails, including ecological sustainability, physical sustainability, economic sustainability, and engendering stewardship. This guide defines seven guiding principles for sustainable trail building: avoiding sensitive ecological areas and critical habitats, developing trails in areas already influenced by human activity, providing buffers to avoid sensitive ecological and hydrologic systems, using natural infiltration and best practices for stormwater management, providing ongoing stewardship of the trails and adjoining natural systems, ensuring that trails are sustainably designed, built, and maintained, and decommissioning and restoring unsustainable trail corridors (Town, n.d.).

There are several key strategies to minimize soil loss and sediment transport into trail-adjacent streams. The tread shape, location, and drainage features should be considered. Trails should be constructed from stable, compacted materials. The tread watershed (the water that lands on and is carried by the tread) can be minimized in several ways. Firstly, avoiding stacking switchbacks (climbing turns) can reduce the off-trail shortcuts taken by trail users. Secondly, signage can be placed along the trail reminding trail users to stay on the designated trail. Grade reversals (spots where the climbing trail goes up and down) can reduce erosion by forcing water to exit the trail at low points throughout the trail. This prevents water from flowing all the way down a climbing trail and thus picking up velocity and sediment. Finally, the frequency of trail maintenance activities is important in keeping trails sustainable and minimizing erosion (Town, n.d.).

1.2.6 Trail Erosion Control Regulations in Vermont

Although the state of Vermont does not have specific laws regulating trail development, there are several regulations that guide trail placement, construction, and maintenance (National, 2020; Recreational, 2020; Stream Alteration Rule, 2017; Vermont Wetland Rules, 2020). The Vermont Department of Environmental Conservation has several sets of regulations guiding any type of development affecting waterways. The Stream Alteration Rule applies to development (including trail building) that takes place in or along streams. If the construction involves movement, excavation, or filling of perennial streams, a permit is required. The purpose of this rule is to prevent flooding and minimize fluvial erosion (Stream Alteration Rule, 2017). The Wetland Rule requires permitting for any development taking place in wetland areas (Vermont Wetland Rules, 2020). The Wetland Rule requires permitting for trail building activities within Class II wetlands and their 50-foot buffer zones, including construction of machine or hand-graded trails, filling for existing trails, filling in wet areas, placement of culverts in streams within the wetland, fording of streams, cutting of woody vegetation for path clearing, placement of pavement, gravel, woodchips, or recycled materials, widening of trails through ditching and other drainage features, or conversion of existing logging roads into trails (Recreational, 2020). Lastly, Construction Stormwater Discharge Permits are required for any trail construction activities that result in a total earth disturbance of one acre or greater, activities with waste load allocations containing pollutants regulated by total maximum daily loads (TMDLs), or activities within geographic areas that contribute to a violation of water quality standards or are significant contributors of aquatic pollutants (National, 2020). There are also local zoning restrictions in many towns that provide more specific regulations for trail building (Town, n.d.). In general, trail-related regulations are dependent on the scale of the development taking place.

1.3 Research Questions & Hypotheses

This study investigated the following questions: Does the character of a trail (age, visitation rate, and trail-stream crossings) influence the average soil incision ratio (depth of incision to trail width) of the trail? Is there a relationship between soil incision ratio and stream-bottom embeddedness? Are trail-adjacent streams subject to impaired water quality, as indicated by macroinvertebrate community composition, when compared to undisturbed forested streams? Table 1 provides an outline of research questions, hypotheses, and guiding references for these hypotheses.

Table 1.
Research questions, hypotheses, and references for this study

Research Question	Hypothesis	References
Does the character of a trail (age, visitation rate, and trail-stream crossings) influence the average soil incision ratio of the trail?	H1: Average soil incision ratio on trails will be related to the trail character (age, visitation rate, and trail-stream crossings).	1. Marion & Wimpey, 2017 2. Meadema et al., 2020 3. Olive & Marion, 2009
Is there a relationship between soil incision ratio and stream-bottom embeddedness?	H2: Stream-bottom embeddedness in trail-adjacent streams will be related to the average soil incision ratio on trail.	1. Johnson et al., 2013 2. Miniat et al., 2019
Are trail-adjacent streams subject to impaired water quality, as indicated by macroinvertebrate community composition, when compared to undisturbed forested streams?	H3: Trail-adjacent streams (particularly in highly trafficked areas) will have a lower water quality index than undisturbed forested streams, as indicated by macroinvertebrate community composition.	1. Berry & Hill, 2003 2. Bona et al., 2016 3. Doretto et al., 2016 4. Johnson et al., 2013 5. Salmaso et al., 2020 6. Wood, 1997

1.4 Site Descriptions

Ten stream sites (nine paired trail-stream sites and one undeveloped forested sites) were monitored over the course of three months (June-August 2021). Data for stream-bottom embeddedness, trail visitation rate, and physical stream parameters (temperature, pH, and stream discharge) were collected six times for each site, with three collections taking place during peak hiking periods (weekends) and three collections during non-peak periods (weekdays). Macroinvertebrate community assessment and trail soil loss measurements were conducted once at each site. Tables 2 and 3 provide background information for each site, and Figure 1 shows the location of each site. Sites 1 and 3 were on State Park land (Camel's Hump State Park and Little River State Park), sites 7-10 were within the Green Mountain National Forest, and the remaining sites were within other public trail networks. Site 10 (George Brook) acted as a control site; there are no established trails along or upstream from the George Brook monitoring site, although the area is open to public recreation and there are several established camping spots along the brook.

Table 2.
Test site trail background information

Site #	Trail Name	Trail Management Organization	Estimated Date of Trail Creation
1	Burrow's Trail & Forest City Trail	VT State Parks & Green Mountain Club (GMC)	1920s
2	Audubon Center Trail Network	Green Mountain Audubon Center	1960s-70s
3	Stevenson Brook Trail	VT State Parks	Not known
4	Catamount Trail - Section 22	Catamount Trail Association	1930s
5	Long Trail / Duxbury Window	GMC	1980s
6	Honey Hollow Trail (Catamount Trail - Section 20)	Catamount Trail Association	1980s
7	Chittenden Brook Trail	Green Mountain National	Not known

		Forest & GMC	
8	Stewart Trail	Blueberry Hill Outdoor Center & Moosalamoo National Recreation Area	mid-1800s
9	Clark Brook Trail	Green Mountain National Forest & GMC	Not known

Table 3.
Physical stream characteristics by site

Site #	Stream Name	Catchment Size Classification	Estimated Stream Gradient (m/km)
1	Brush Brook	Small Stream	187
2	Sherman Hollow Brook	Small Stream	22
3	Stevenson Brook	River	125
4	Michigan Brook	Small Stream	148
5	Gleason Brook	River	170
6	Preston Brook	River	89
7	Chittenden Brook	Small Stream	151
8	Dutton Brook	Small Stream	138
9	Clark Brook	River	119
10	George Brook	Small Stream	197

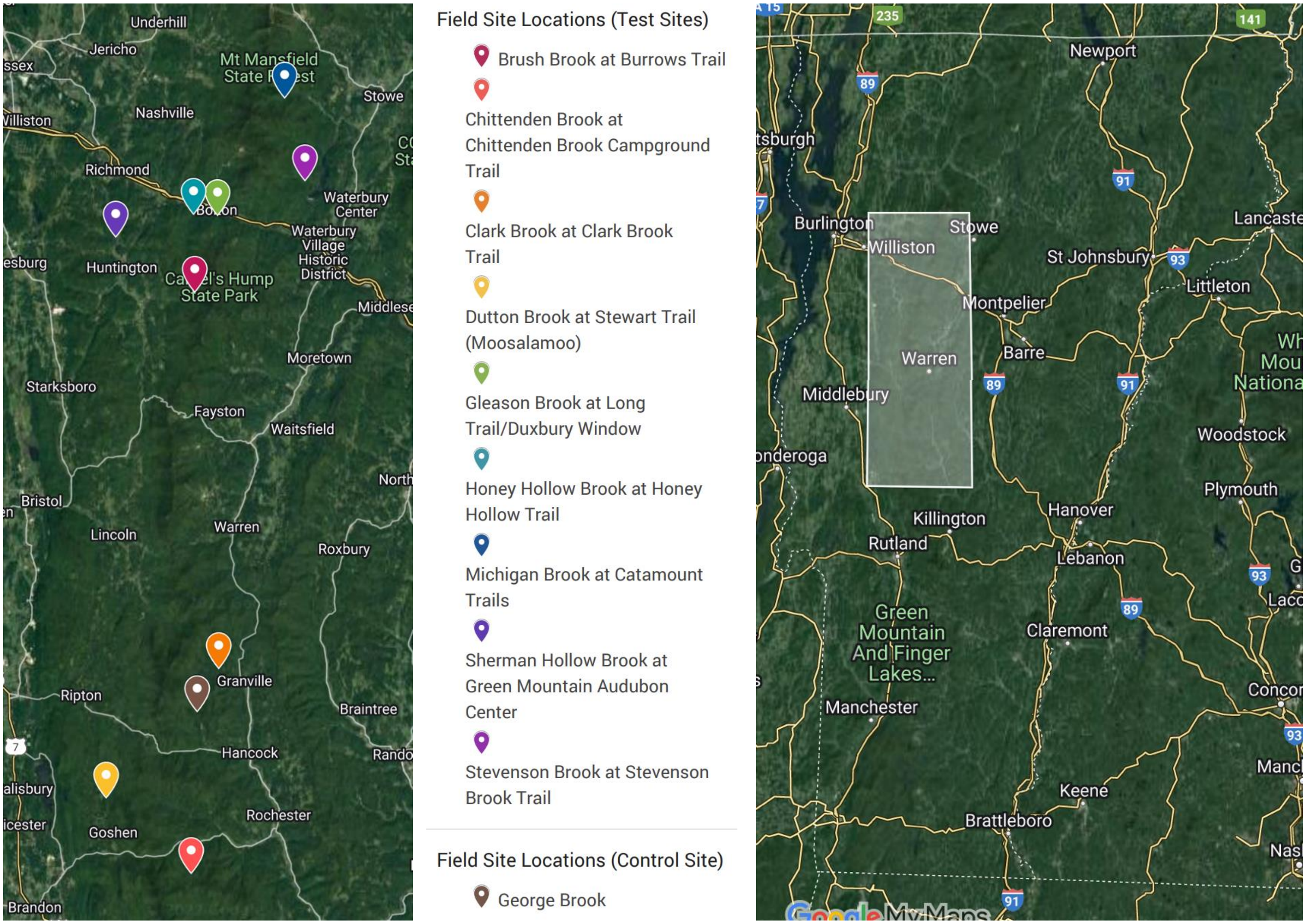

Figure 1. Field site location map

2. Methods

2.1 Site Selection

Study sites were determined using the following characteristics:

a. First order, rocky-bottom streams

b. Adjacent to publicly managed, publicly accessible hiking trails

c. Within the state of Vermont and within a 65-mile radius of Burlington, VT

d. *Control site: one stream site in an undeveloped forested area*

2.2 Trail Characteristics

2.2.1 Trail Age

Trail age was measured as the number of years since significant trail work. In the context of this study, trail work was defined as significant tread or erosion work that requires trail closures or re-routing. These data were acquired from trail management organizations (B. Clark, personal communication, November 19, 2021; K. Tierney, personal communication, February 2, 2021; M. Williams, personal communication, October 5, 2021).

2.2.2 Visitation Rate

Trail visitation rate was measured as visitors per hour. The number of hikers was counted at each site visit, then divided by the duration of the visit to determine visitation rate. Site visits were evenly divided between peak hiking periods (weekends) and non-peak periods (weekdays) to accurately represent overall visitation.

2.2.3 Number of Stream Crossings

Stream crossings were defined as areas where the managed trail crossed areas of active stream flow. Stream crossings were sorted into three categories; direct crossings (where the trail leads through the stream), culverts (where water is directed through a pipe under the trail), and raised bridges (where the trail leads over the stream on a raised structure) (Figure 2).

Figure 2. Types of stream crossings

2.3 Soil Incision Ratio

Previous studies have measured the cross-sectional area of soil loss on trails (Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009). Cross-sectional area is measured by determining the width of the trail and measuring the depth of incision at multiple points across the trail to determine the volume of soil that has been eroded away. Because there was a large variation in trail width across the study sites, soil incision ratio (average depth of incision divided by trail width) was used in the current study to standardize results. Soil incision was measured at four points along each trail (at the trailhead, near the stream study site, and at high and low trail slopes) and averaged to determine a single result for each site. Soil incision was not measured for site 7 (Chittenden Brook) due to temporary trail closures during the monitoring period.

2.4 Stream Health Assessment

2.4.1 Stream-Bottom Embeddedness

Stream-bottom embeddedness was measured through visual estimation of the percentage of coarse substrate (rocks, cobble, boulders, and bedrock) covered by fine sediment. Embeddedness estimates were conducted using a variation of the Platts-Bain Visual Method; five coarse particulates (rocks) within the stream reach were selected at random, and the percent coverage of fine sediments was estimated to the nearest ten percent (Sennatt et al., 2007). These estimates were averaged to determine a single embeddedness value for each stream, including the control site. Water samples were collected at each site visit and analyzed in the laboratory using a vacuum pump system to determine average total suspended solids concentration at each site. Turbidity was measured at each site visit using a transparency tube (Anderson & Davie, 2004). However, total suspended solids concentrations and turbidity levels were consistently below detection limits and were not used in the analyses.

2.4.2 Macroinvertebrate Community Assessment

Macroinvertebrate community assessment was conducted using the methods laid out by the Water Action Volunteer program through the University of Wisconsin-Madison (University). Macroinvertebrates were collected using a kick net at three points along the stream reach; two riffle areas and one relatively still-water area. The net was placed in each sampling point for 1-2 minutes, and the substrate within the 2025 cm^2 square upstream of the net was kicked and scrubbed to dislodge macroinvertebrates. Macroinvertebrates were identified to the order in the field to determine community composition through presence or absence of particular orders. Community composition was used as an indicator of stream health and level of impairment, according to the Water Action Volunteer program index (University). Through this index, the impairment level was classified for each site as "Good", "Fair", or "Poor" based on how many sensitive, semi-sensitive, semi-tolerant, and tolerant species were present.

2.5 Statistical Methods

Three separate analyses were conducted using the study data; soil incision ratio v. trail characteristics, embeddedness v. incision ratio, and embeddedness v. estimated stream gradient. The analysis of trail characteristics was conducted using a multiple linear regression, and the analyses of embeddedness were conducted using linear regression models. The data were tested for linearity, normal distribution, and homoscedasticity to ensure that linear regression could be used. All analysis and modeling was conducted using R software. The code used in this

3. Results

3.1 Incision Ratio & Trail Characteristics

Table 4 shows the measured trail characteristics: trail age (the number of years since significant trail work has been conducted), average visitation rate (visitors per hour), and the total number of trail-stream crossings. The partial regression analysis of trail character and soil incision ratio did not find any significant relationships (Figures 3-5). Only five sites were analyzed in this multiple regression set due to lack of data on trail age.

Trail characteristics (age, visitation, and crossings) by site

Site #	Trail Name	Trail Age (years since trail work)	Average Visitation Rate & Range (visitors/hour)	Number of Trail-Stream Crossings
1	Burrow's Trail & Forest City Trail	1	4.3 *(0-7)*	19
2	Audubon Center	2	4.5	5

	Trail Network		*(0-10)*	
3	Stevenson Brook Trail	Not known	5.9 *(0-23)*	33
4	Catamount Trail - Section 22	3	0 *(0)*	3
5	Long Trail / Duxbury Window	Not known	10 *(3-19)*	6
6	Honey Hollow Trail (Catamount Trail - Section 20)	3	2.1 *(0-3)*	33
7	Chittenden Brook Trail	Not known	0.5 *(0-3)*	Not known
8	Stewart Trail	2	1.2 *(0-4)*	8
9	Clark Brook Trail	Not known	5.2 *(2-10)*	10

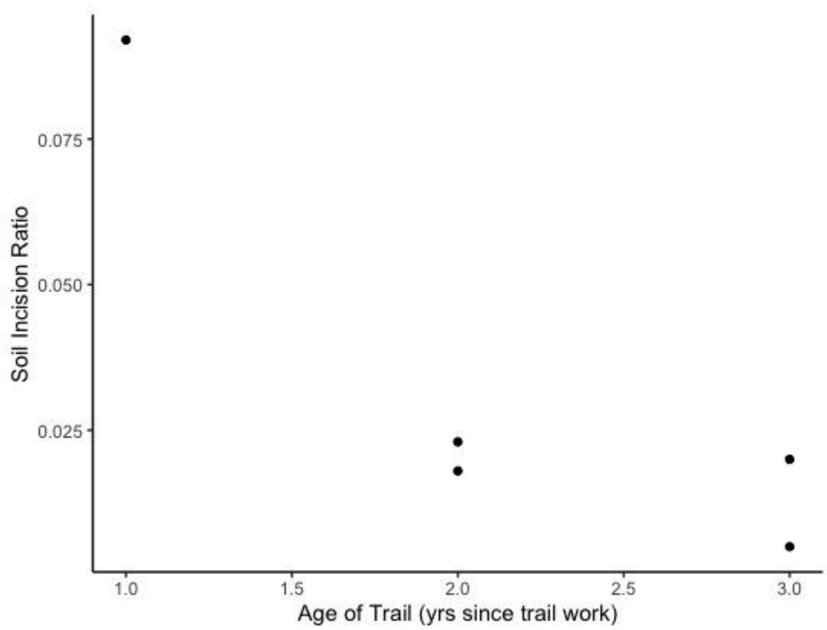

Figure 3. Soil incision ratio v. age of trail (n=5, p=0.064, R^2=0.79)

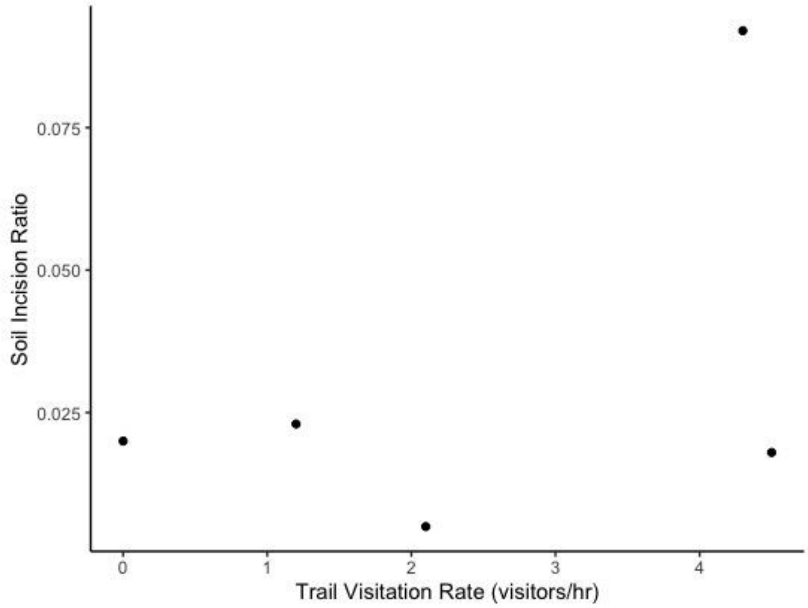

Figure 4. Soil incision ratio v. trail visitation rate (n=5, p=0.716, R^2=0.79)

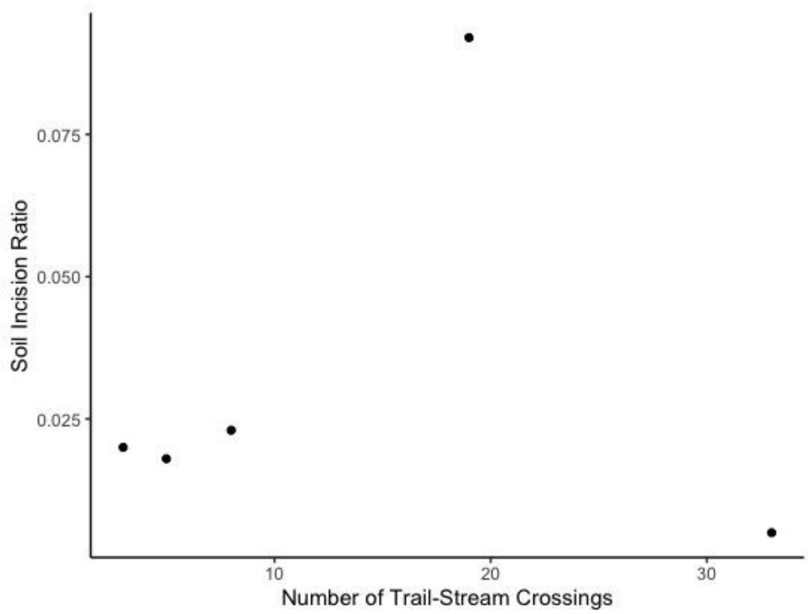

Figure 5. Soil incision ratio v. number of trail-stream crossings (n=5, p=0.741, R^2=0.79)

3.2 Embeddedness & Incision Ratio

The average soil incision ratio ranged from 0.005 to 0.092 (Table 5). There was a wide range for stream embeddedness, with sites ranging from 12 percent to 41 percent (Table 6). The control site (George Brook) fell within this range, at 14 percent embeddedness on average.

According to the EPA, 0 to 25 percent embeddedness is optimal habitat in high gradient streams, while 25 to 50 percent is considered suboptimal (Barbour et al., n.d.). Four of the test sites fell into this suboptimal category. There was a slight negative trend observed between soil incision ratio and stream embeddedness (Figure 6). However, there was not a significant relationship found ($p=0.389$). This indicates that there were likely other factors influencing stream-bottom embeddedness.

Table 4.
Average soil incision ratio by site

Site #	Trail Name	Average Soil Incision Ratio
1	Burrow's Trail & Forest City Trail	0.092
2	Audubon Center Trail Network	0.028
3	Stevenson Brook Trail	0.014
4	Catamount Trail - Section 22	0.02
5	Long Trail / Duxbury Window	0.046
6	Honey Hollow Trail (Catamount Trail - Section 20)	0.005
7	Chittenden Brook Trail	Not known
8	Stewart Trail	0.023
9	Clark Brook Trail	0.068

Table 5.
Average stream-bottom embeddedness, total suspended solids, and turbidity by site

Site #	Stream Name	Average Stream-Bottom Embeddedness (%)	Average Total Suspended Solids (TSS) (mg/L)	Average TSS as Determined by Turbidity (mg/L)
1	Brush Brook	22	0.88	<10
2	Sherman Hollow Brook	41	0.242	<10

3	Stevenson Brook	14	Below detection limit (negative)	<10
4	Michigan Brook	22	Below detection limit (negative)	<10
5	Gleason Brook	12	Below detection limit (negative)	<10
6	Preston Brook	33	Below detection limit (negative)	<10
7	Chittenden Brook	27	Below detection limit (negative)	<10
8	Dutton Brook	40	0.23	<10
9	Clark Brook	22	Below detection limit (negative)	<10
10	George Brook	15	0.14	<10

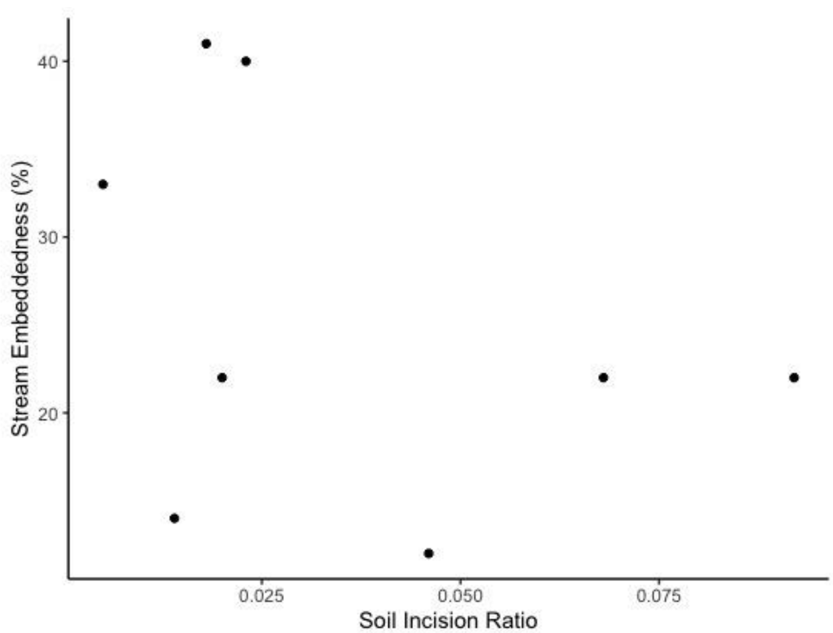

Figure 6. Stream-bottom embeddedness v. soil incision ratio (n=8, p=0.389, R^2=0.13)

3.3 Embeddedness & Stream Gradient

There was a negative relationship between stream gradient and embeddedness (Figure 7). This relationship was found to be statistically significant (p=0.032), although this analysis also contained a few clear outliers.

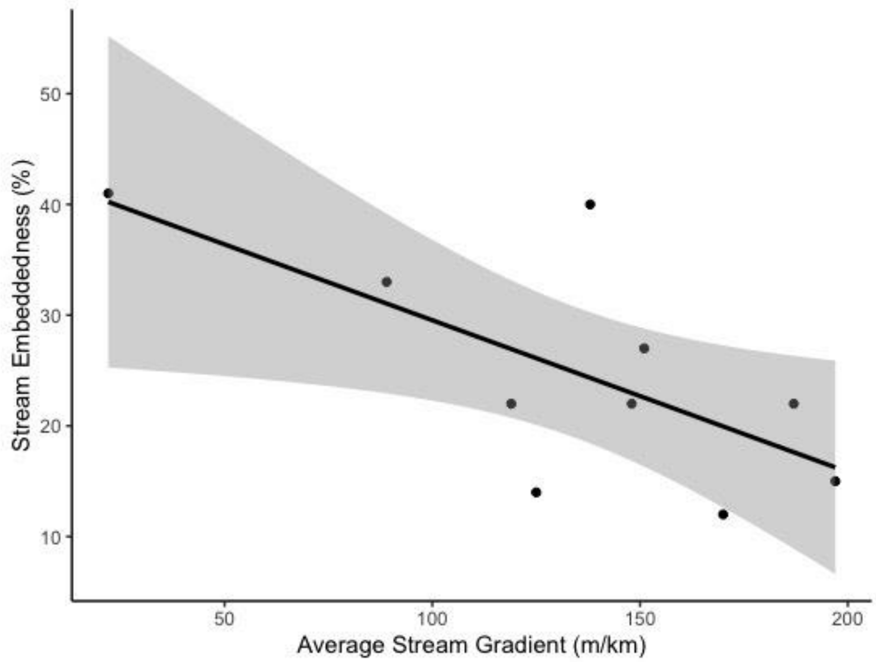

Figure 7. Stream embeddedness v. stream gradient; shaded region represents 95% confidence interval for linear regression (n=10, p=0.032, R^2=0.46)

3.4 Macroinvertebrates & Stream Health

Macroinvertebrate community composition was relatively similar between sites. Table 7 shows the pollution score index, score meaning, and macroinvertebrate taxa present at each stream site. The majority of species found at each site fell into the semi-sensitive group (Table 7). Nine out of ten sites were classified as “Good” using the Water Action Volunteers index. The exception was Sherman Hollow Brook, which was classified as “Fair”.

Table 6.
Results of macroinvertebrate community composition analysis by site

Site #	Stream Name	Pollution Index Score	Score Meaning (Good, Fair, Poor)	Macroinvertebrates Present
1	Brush Brook	3.25	Good	Stonefly larva, crane fly larva, mayfly larva, damselfly larva
2	Sherman Hollow Brook	2.33	Fair	Stonefly larva, crane fly larva, mayfly larva, crawfish, bloodworm midge larva
3	Stevenson Brook	3.4	Good	Stonefly larva, alderfly larva, caddisfly larva, mayfly larva, riffle beetle larva
4	Michigan Brook	3.17	Good	Stonefly larva, alderfly larva, caddisfly larva, mayfly larva, riffle beetle adult, non-red midge larva
5	Gleason Brook	3	Good	Stonefly larva, caddisfly larva, mayfly larva, crawfish, non-red midge larva
6	Preston Brook	3.2	Good	Stonefly larva, caddisfly larva, crane fly larva, mayfly larva, riffle beetle larva
7	Chittenden Brook	3.3	Good	Stonefly larva, mayfly larva, damselfly larva
8	Dutton Brook	3	Good	Stonefly larva, caddisfly larva, crane fly larva, mayfly larva, non-red midge larva
9	Clark Brook	3.25	Good	Stonefly larva, caddisfly larva, mayfly larva, riffle beetle larva
10	George Brook	3.2	Good	Stonefly larva, caddisfly larva, crane fly larva, mayfly larva, damselfly larva

4. Discussion

This study was conducted to better understand and quantify the relationships between trail character, soil incision, and stream-bottom embeddedness. This was done using two main analyses; examining potential relationships between trail character (age, visitation rate, and number of trail-stream crossings) and soil incision ratio, examining the potential relationship between soil incision ratio and stream-bottom embeddedness, and using macroinvertebrate community composition to quantify stream impairment levels. Overall, these analyses suggested that trail-adjacent stream habitats were not subject to high levels of disturbance associated with the presence and use of hiking trails.

4.1 Soil Incision Ratio & Trail Characteristics

The analysis suggests that trail characteristics did not have a significant influence on soil loss on trails, as measured through soil incision ratio.

Trail age data were limited due to the lack of available records of ongoing trail work. However, all trails for which age was able to be determined had significant trail work within the past three years, and it is possible that soil erosion processes due to trail aging occur over greater time scales than those measured in the current study. The type of trail maintenance actions being conducted may have more influence on soil loss than the frequency of maintenance, according to a study conducted along the Appalachian Trail (Marion & Wimpey, 2017).

The trail sites in the current study were primarily used for hiking, and visitation rate was measured by the rate of hikers using the trail during the sampling period. However, it is possible that other types of use were present on some trails, such as mountain biking or cross-country skiing. A study by Olive & Marion examined hiking trails, horse trails, and off-vehicle trails and found that the type of use had a considerable effect on the severity of soil loss (2009). Although the current study was primarily focused on the impact of hiking, it is possible that other types of trail use (past and present) had an influence on soil loss patterns.

It was thought that the number of trail-stream crossings present would increase soil incision. Unpaved stream crossings (culverts and bridges) were associated with increased sediment yields in streams, according to a study in the Choctawhatchee watershed (Witmer et al., 2009). This suggests that soil was being eroded into streams at trail crossings. The amount of sediment deposition resulting from trail-stream crossings may be dependent on the type of crossings present, with raised bridges resulting in lower stream sediment levels than culverts (Aust et al., 2011). The influence of different types of trail-stream crossings was not analyzed in the current study, but there was a large variety in crossing types across the sites. It is possible that the types of stream crossings present, including many raised bridges, influenced the levels of soil erosion on trails. Forestry best management practices (BMPs) can also reduce the amount of soil erosion and sediment deposition in streams, particularly during rainfall events (Morris et al., 2016). Although forestry best management practices were not specifically examined in the current study, it is possible that the sustainable trail building and maintenance practices in place minimized the soil erosion associated with stream-crossings.

Lastly, several studies of soil loss on hiking trails suggested that trail layout (including trail grade, slope alignment, and tread drainage features) is a key determinant of soil loss (Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009). It is possible that the soil incision ratios of the studied trail sites could have been explained by differences in trail layout.

4.2 Embeddedness & Soil Incision Ratio

Average embeddedness ranged from 12 percent to 41 percent, with the control site (George Brook) being among the lowest values. Four of the test sites fell into the suboptimal habitat category based on stream-bottom embeddedness, while the remaining five test sites and the control site were within the optimal range. This may suggest that there has been some alteration of natural sediment dynamics in the sites measured as suboptimal. However, natural processes like localized flooding events, snow melt levels, and channel morphology could have also been responsible for elevated sediment levels (Hassan et al., 2005; Lenzi & Marchi, 2000). It is important to note that the control site was located within the Green Mountain National Forest. While there is not an established trail network at or upstream from the site, the land is open to public recreation, including hiking, fishing, camping, and off-road vehicle use. Because of this, the sediment regime of George Brook may have also been influenced by recreation, even though there was not a designated trail.

Stream-bottom embeddedness was not found to be significantly related to soil incision ratio. This analysis suggests that the soil erosion associated with trail building and use has not significantly altered stream habitat. As discussed in the introduction, trail building and maintenance in Vermont is subject to several sets of regulations, including the Stream Alteration Rule, the Vermont Wetland Rule, and construction stormwater permitting rules (National, 2020; Recreational, 2020; Stream, 2017; Wetland, 2020). The results of this study have possible implications for recreation management; this study may suggest that the current regulations and practices for trail development and erosion control are effective in protecting forested stream habitats from sedimentation.

4.3 Embeddedness & Stream Gradient

Stream gradient and discharge are two of the main natural drivers of sediment regimes in first-order, high gradient streams (Dewey et al., 2020; Lenzi et al., 2003). The results indicate that the average stream-bottom embeddedness decreased with increasing elevational gradient.

Steeper streams are generally associated with increased flow rate, meaning that a greater volume of water is being flushed through the stream basin at any given time. This may explain why steeper streams generally have reduced embeddedness values; sediment is being carried through streams more quickly and is less likely to settle. These results indicate that the sediment levels in the studied streams could be explained by natural processes rather than by on-trail soil loss. This suggests that the trail-adjacent streams were functioning similarly to undeveloped streams, meaning that trail use and associated soil loss was not significantly altering natural stream processes.

4.4 Macroinvertebrates & Stream Health

Macroinvertebrate community composition analyses suggest that none of the study sites were impaired. Sensitive taxa were found at many sites, suggesting that these streams provide important habitat for pollution-sensitive macroinvertebrates. Several studies suggest that headwater streams provide important habitats for sensitive macroinvertebrate taxa and host diverse macroinvertebrate communities (Clarke et al., 2008; Ferreira et al., 2014; Heino, 2005). This highlights the importance of continuing to monitor the impact of recreation and development on headwater streams. Overall, the macroinvertebrate community analysis suggests that macroinvertebrate communities were not severely impacted by public hiking trail use.

4.5 Further Research

4.5.1 Long-Term Paired Trail-Stream Studies

This study was conducted over a period of three months. Further studies could better describe the long-term effects of public hiking trail construction and use by monitoring stream sites from trail construction through trail aging. This would allow for a more comprehensive understanding of how trails impact their surrounding landscape throughout their lifespans. Studies could also take place across different soil gradients to account for the different erosional patterns of different soil types (Wakindiki & Ben-Hur, 2002).

4.5.2 Measuring Sediment & Embeddedness in Low-Sediment Streams

One of the challenges of this study was accurately describing sediment regimes in headwater streams. Total suspended solids and turbidity were found to be inadequate measures of sediment because it was not possible to determine accurate values with the sensitivity of the instrumentation used (Table 6). Stream-bottom embeddedness could provide a more accurate metric for sediment dynamics. Further studies could seek to determine which metrics are most useful in describing sediment levels in low-sediment streams.

4.5.3 Applications and Uses of Metrics for Soil Loss & Erosion

Soil incision ratio was used in this study to describe the extent of soil loss on trails, whereas other studies have used cross-sectional area as a measure of soil loss (Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009). Soil incision ratio provides a means of standardizing results across trails of different widths. To provide a comprehensive assessment of trail impact, soil incision ratio should be measured across a variety of other sites and validated using other quantitative measurements of soil erosion.

5. Conclusion

Based on the results of this study, the presence and use of public hiking trails in Vermont is not associated with measurable headwater stream degradation through alteration of sediment regimes or resultant changes in macroinvertebrate community composition. Soil incision is present on trails, but it does not appear to be significantly affected by the elements of trail character measured in this study (trail age, visitation rate, and number of trail-stream crossings). These results may suggest that current trail development regulations in Vermont are effective in reducing erosion. Given the importance and prevalence of outdoor recreation in Vermont, it is important to understand the ecological impacts of hiking trails and other recreation infrastructure. More research is necessary to better recognize the relationship between public hiking trail development and use, soil loss, sediment dynamics in trail-adjacent streams, and stream health. Future work could seek to identify the most effective means of measuring soil loss on trails and stream sediment levels in forested headwater streams.

Appendix

This appendix contains the code used in R to analyze potential relationships in the data and create figures.

<u>Code Used for Hypothesis 1</u>

```
#summary of data
summary(analysisA)

#check whether linear regression can be used

#check for correlation between independent variables
cor(analysisA[c("age", "crossings", "visitation")])

#normal distribution
Incision <- analysisA$incision
hist(Incision)

#linearity
#age and incision
plot(incision ~ age, data = analysisA)

#crossings and incision
plot(incision ~ crossings, data = analysisA)

#visitation and incision
plot(incision ~ visitation, data = analysisA)

#linear regression
lmIncision <- lm(incision ~ age + crossings + visitation, data = analysisA)

#get summary
summary(lmIncision)

#check for homoscedasticity
par(mfrow=c(2,2) )
plot(lmIncision)
par(mfrow=c(1,1) )

#plot results
analysisAgraph1 <- ggplot(analysisA, aes(x=age, y=incision) ) +
  geom_point()

analysisAgraph1
```

```
analysisAgraph1 +
  theme_classic() +
  labs(x = "Age of Trail (yrs since trail work)",
       y = "Soil Incision Ratio")

analysisAgraph2 <- ggplot(analysisA, aes(x=crossings, y=incision) ) +
 geom_point()

analysisAgraph2

analysisAgraph2 +
 theme_classic() +
 labs(x = "Number of Trail-Stream Crossings",
      y = "Soil Incision Ratio")

analysisAgraph3 <- ggplot(analysisA, aes(x=visitation, y=incision) ) +
 geom_point()

analysisAgraph3

analysisAgraph3 +
 theme_classic() +
 labs(x = "Trail Visitation Rate (visitors/hr)",
      y = "Soil Incision Ratio")

#linear regression isolating trail age
lmTrailAge <- lm(incision ~ age, data=analysisA)

#get summary
summary(lmTrailAge)
```

<u>Code Used for Hypothesis 2</u>

```
#summary of data
summary(analysisB)

#check whether linear regression can be used

#normal distribution
Embeddedness <- analysisB$embeddedness
hist(Embeddedness)

#linearity
plot(embeddedness ~ incision, data = analysisB)
```

```
#linear regression
lmEmbeddedness <- lm(embeddedness ~ incision, data = analysisB)

#get summary
summary(lmEmbeddedness)

#check for homoscedasticity
par(mfrow=c(2,2) )
plot(lmEmbeddedness)
par(mfrow=c(1,1) )

analysisBgraph <- ggplot(analysisB, aes(x=incision, y=embeddedness) ) +
  geom_point()

analysisBgraph

analysisBgraph +
  theme_classic() +
  labs(x="Soil Incision Ratio",
       y="Stream Embeddedness (%)")
```

<u>Other Code Used for Analysis & Figures</u>

```
#summary of data
summary(analysisC)

#check whether linear regression can be used

#normal distribution
Embeddedness <- analysisC$embeddedness
hist(Embeddedness)

#linearity
plot(embeddedness ~ gradient, data = analysisC)

#linear regression
lmEmbeddednessG <- lm(embeddedness ~ gradient, data = analysisC)

#get summary
summary(lmEmbeddednessG)

#check for homoscedasticity
par(mfrow=c(2,2) )
plot(lmEmbeddednessG)
par(mfrow=c(1,1) )
```

```
#plot results
analysisCgraph <- ggplot(analysisC, aes(x=gradient, y=embeddedness) ) +
  geom_point()

analysisCgraph

analysisCgraph2 <- analysisCgraph + geom_smooth(method="lm", col="black")

analysisCgraph2

analysisCgraph2 +
  theme_classic() +
  labs(x="Average Stream Gradient (m/km)",
       y="Stream Embeddedness (%)")
```

Works Cited

Anderson, P., & Davie, R. D.. (2004). Use of Transparency Tubes for Rapid Assessment of Total Suspended Solids and Turbidity in Streams. *Lake and Reservoir Management*, *20*(2), 110–120. https://doi.org/10.1080/07438140409354355

Assouline, S., & Ben-Hur, M.. (2006). Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. *CATENA*, *66*(3), 211-220. https://doi.org/10.1016/j.catena.2006.02.005

Ault, K., & Dagger, J.. (2021, Nov 18). *Federal data report: Vermont outdoor recreation sector stood tall as significant economic driver during shutdowns of 2020*. Vermont Agency of Natural Resources. Retrieved from: https://fpr.vermont.gov/news/federal-data-outdoor-recreation-sector-vermont-2020

Aust, W. M., Carroll, M. B., Bolding, M. C., & Dolloff, C. A.. (2011). Operational forest stream crossings effects on water quality in the Virginia Piedmont. *Southern Journal of Applied Forestry*, *35*(3), 123–130. https://doi.org/10.1093/sjaf/35.3.123

Barbour, M.T., Gerritsen, J., Snyder, B.D., Stribling, J.B.. (n.d.) Habitat assessment and physicochemical parameters. In *Rapid bioassessment protocols for use in streams and wadeable rivers: Periphyton, benthic macroinvertebrates, and fish* (2nd ed.). Environmental Protection Agency. Retrieved from: https://archive.epa.gov/water/archive/web/html/ch05b.html

Berry, W., & Hill, B.. (2003). The biological effects of suspended and bedded sediment (SABS) in aquatic systems: A review. *U.S. EPA Archives.* Retrieved from: https://archive.epa.gov/epa/sites/production/files/2015-10/documents/sediment-appendix1.pdf

Bona, F., Doretto, A., Falasco, E., La Morgia, V., Piano, E., Ajassa, R., & Fenoglio, S.. (2016). Increased sediment loads in alpine streams: An integrated field study. *River Research and Applications*, *32*(6), 1316–1326. https://doi.org/10.1002/rra.2941

Clarke, A., Mac Nally, R., Bond, N., & Lake, P. S.. (2008). Macroinvertebrate diversity in headwater streams: a review. *Freshwater Biology*, *53*(9), 1707–1721. https://doi.org/10.1111/j.1365-2427.2008.02041.x

Cover, M.R., May, C.L., Dietrich, W.E., & Rech, V.H.. (2008). Quantitative linkages among sediment supply, streambed fine sediment, and benthic macroinvertebrates in northern California streams. *Freshwater Systems*, *27*(1). https://doi.org/10.1899/07-032.1

Dewey, J., Hatten, J., Choi, B., Mangum, C., & Ouyang, Y.. (2020). Climate drivers and sources of sediment and organic matter fluxes in intermittent rivers and ephemeral streams (IRES) of a subtropical watershed, USA. *Climate*, *8*(10), 117. https://doi.org/10.3390/cli8100117

Doretto, A., Bona, F., Falasco, E., Piano, E., Tizzani, P., & Fenoglio, S.. (2016). Fine sedimentation affects CPOM availability and shredder abundance in Alpine streams. *Journal of Freshwater Ecology*, *31*(2), 299–302. https://doi.org/10.1080/02705060.2015.1124297

Ferreira, W.R., Ligeiro, R., Macedo, D.R., Hughes, R.M., Kaufmann, P.R., Oliveira, L.G., Callisto, M.. (2014). Importance of environmental factors for the richness and distribution of benthic macroinvertebrates in tropical headwater streams. *Freshwater Science*, *33*(3), 860-871. https://doi.org/10.1086/676951

Hassan, M. A., Church, M., Lisle, T. E., Brardinoni, F., Benda, L., & Grant, G. E.. (2005). Sediment transport and channel morphology of small, forested streams. *Journal of the American Water Resources Association*, *41*(4), 853–876. https://doi.org/10.1111/j.1752-1688.2005.tb04467.x

Heino, J.. (2005), Functional biodiversity of macroinvertebrate assemblages along major ecological gradients of boreal headwater streams. *Freshwater Biology*, *50*, 1578-1587. https://doi.org/10.1111/j.1365-2427.2005.01418.x

Hofmeister, K. L., Nave, L. E., Drevnick, P., Veverica, T., Knudstrup, R., Heckman, K. A., Riha, S. J., Schneider, R. L., & Walter, M. T.. (2019). Seasonal dynamics and exports of elements from a first-order stream to a large inland lake in Michigan. *Hydrological Processes*, *33*(10), 1476–1491. https://doi.org/10.1002/hyp.13416

Johnson, L., & Student Conservation Association. (2013). Mammoth Cave National Park Backcountry Trail and Stream Monitoring, 2009-2012. *Mammoth Cave Research Symposia*(Paper 21). Retrieved from: https://digitalcommons.wku.edu/cgi/viewcontent.cgi?article=1091&context=mc_reserch_symp

Lenzi, M. A., Mao, L., & Comiti, F.. (2003). Interannual variation of suspended sediment load and sediment yield in an alpine catchment. *Hydrological Sciences Journal*, *48*(6), 899–915. https://doi.org/10.1623/hysj.48.6.899.51425

Lenzi, M. A., & Marchi, L. (2000). Suspended sediment load during floods in a small stream of the Dolomites (northeastern Italy). *CATENA*, *39*(4), 267-282. https://doi.org/10.1016/S0341-8162(00)00079-5

Marion, J. L., & Wimpey, J.. (2017). Assessing the influence of sustainable trail design and maintenance on soil loss. *Journal of Environmental Management*, *189*, 46–57. https://doi.org/10.1016/j.jenvman.2016.11.074

Mathers, K. L., Collins, A. L., England, J., Brierley, B., & Rice, S. P.. (2017). The fine sediment conundrum; quantifying, mitigating and managing the issues. *River Research and Applications*, *33*(10), 1509–1514. https://doi.org/10.1002/rra.3228

McLane, K. (2021, March 25). *Mud season conditions are here*. Green Mountain Club. Retrieved from: https://www.greenmountainclub.org/vermont-mud-season-arrived/

Meadema, F., Marion, J. L., Arredondo, J., & Wimpey, J.. (2020). The influence of layout on

Appalachian Trail soil loss, widening, and muddiness: Implications for sustainable trail design and management. *Journal of Environmental Management*, *257*, 109986. https://doi.org/10.1016/j.jenvman.2019.109986

Miniat, C. F., Clinton, P. P., & Everage, L. K.. (2019). The effects of off-highway vehicle trails and use on stream water quality in the north fork of the Broad River. *Transactions of the ASABE*, *62*(2), 539–548. https://doi.org/10.13031/trans.13098

Monz, C. A., Pickering, C. M., & Hadwen, W. L.. (2013). Recent advances in recreation ecology and the implications of different relationships between recreation use and ecological impacts. *Frontiers in Ecology and the Environment*, *11*(8), 441–446. https://doi.org/10.1890/120358

Morris, B., Bolding, M., Aust, W., Mcguire, K., Schilling, E., & Sullivan, J.. (2016). Differing Levels of Forestry Best Management Practices at Stream Crossing Structures Affect Sediment Delivery and Installation Costs. *Water*, *8*(3), 92. https://doi.org/10.3390/w8030092

Olive, N. D., & Marion, J. L.. (2009). The influence of use-related, environmental, and managerial factors on soil loss from recreational trails. *Journal of Environmental Management*, *90*(3), 1483–1493. https://doi.org/10.1016/j.jenvman.2008.10.004

Salmaso, F., Crosa, G., Espa, P., Gentili, G., & Quadroni, S.. (2020). The year after an extraordinary sedimentation event in a regulated Alpine river: The impact on benthic macroinvertebrate communities. *River Research and Applications*, *36*(8), 1656–1667. https://doi.org/10.1002/rra.3664

Sennatt, K. M., Salant, N. L., Renshaw, C. E., & Magilligan, F. J.. (2006). Assessment of methods for measuring embeddedness: Application to sedimentation in flow regulated streams. *Journal of the American Water Resources Association*, *42*(6), 1671–1682. https://doi.org/10.1111/j.1752-1688.2006.tb06028.x

United States Forest Service. (Sep 2016). Trail fundamentals & trail management objectives. U.S. Department of Agriculture. Retrieved from: https://www.fs.fed.us/recreation/programs/trail-management/documents/trailfundamentals/1623-3801_TrailFdml+TMO_Sec508_11-14-16_150dpi.pdf

University of Wisconsin-Madison and Wisconsin Department of Natural Resources. Citizen Monitoring Biotic Index. Retrieved from: https://wateractionvolunteers.org/files/2019/10/BioticIndexMethods-2015update.pdf

Vermont Department of Environmental Conservation. (2017, Mar 10). Environmental Protection Rule Ch. 27 - Stream Alteration Rule. Retrieved from: https://dec.vermont.gov/sites/dec/files/documents/wsmd_StreamAlterationRule_2017-03-10.pdf

Vermont Department of Environmental Conservation. (2020, Jan 21). Environmental Protection

Rule Ch. 30 - Vermont Wetland Rules. Retrieved from: https://dec.vermont.gov/sites/dec/files/documents/wsmd_VermontWetlandRules.pdf

Vermont Department of Environmental Conservation. (2020, Feb 19). *National pollutant discharge elimination system (NPDES): General permit 3-9020 for stormwater runoff from construction sites.* Vermont Agency of Natural Resources. Retrieved from: https://dec.vermont.gov/sites/dec/files/documents/3-9020_Stormwater_ConstructionGeneralPermit_2020-02-19.pdf

Vermont Department of Environmental Conservation. (2020, June 12). *Recreational trail building and wetlands*. Vermont Agency of Natural Resources. Retrieved from: https://dec.vermont.gov/sites/dec/files/wsm/wetlands/docs/WTLD_TrailGuidance.pdf

Vermont outdoor recreation economy report. (2017, July 26). Outdoor Industry Association. Retrieved from: https://outdoorindustry.org/resource/vermont-outdoor-recreation-economy-report/

Vermont Town Forests. *Trail Design Guide*. https://vtcommunityforestry.org/sites/default/files/pictures/Town_Forest_Toolkit/Implementation_Pod/trail_design_guide.pdf. PowerPoint Presentation.

Wakindiki, I. I. C., & Ben-Hur, M. (2002). Soil mineralogy and texture effects on crust micromorphology, infiltration, and erosion. *Soil Science Society of America Journal*, *66*(3), 897-905. Retrieved from: https://www-proquest-com.ezproxy.uvm.edu/docview/216055283/fulltext/A855599CDB54C4CPQ/1?accountid=14679

Witmer, P.L., Stewart, P.M. and Metcalf, C.K. (2009), Development and use of a sedimentation risk index for unpaved road-stream crossings in the Choctawhatchee watershed. JAWRA Journal of the American Water Resources Association, 45: 734-747. https://doi-org.ezproxy.uvm.edu/10.1111/j.1752-1688.2009.00319.x

Wohl, E., Bledsoe, B. P., Jacobson, R. B., Poff, N. L., Rathburn, S. L., Walters, D. M., & Wilcox, A. C.. (2015). The natural sediment regime in rivers: Broadening the foundation for ecosystem management. *Bioscience*, *65*(4), 358–371. https://doi.org/10.1093/biosci/biv002

Wood, P. J.. (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management*, *21*(2), 203–217. https://doi.org/10.1007/s002679900019

Yamada, H., & Nakamura, F.. (2009). Effects of fine sediment accumulation on the redd environment and the survival rate of masu salmon (Oncorhynchus masou) embryos. *Landscape and Ecological Engineering*, *5*(2), 169–181. https://doi.org/10.1007/s11355-009-0065-8