The Influence of Layout on Degradation of the Appalachian Trail

Fletcher Meadema

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Forest Resources and Environmental Conservation

Jeff Marion
Yang Shao
Jeremy Wimpey

September 6, 2018
Blacksburg, Virginia

Keywords: Recreation Ecology, Sustainable Trail Management, Sustainable Trail Design, Trail Degradation, Trail Soil Loss, Trail Widening, Trail Muddiness, Appalachian Trail
The Influence of Layout on Degradation of the Appalachian Trail

Fletcher Meadema

GENERAL AUDIENCE ABSTRACT

Natural surfaced trails are an essential infrastructure component in parks and protected natural areas. They provide transportation routes through otherwise undeveloped areas and outdoor recreation opportunities for hikers, mountain bikers, and equestrians. Over time, recreational use and natural processes such as rainfall can lead to negative ecological impacts that damage trail treads in ways that impair their utility for visitors and require costly repairs. Environmental factors like unstable soils or extreme precipitation can make trails more susceptible to degradation. However, sustainable trail layouts and effective maintenance can reduce the rate and severity of degradation. This research investigates the influence of trail layout on three chief forms of trail degradation: trail soil loss, muddiness, and widening.

Many trail science studies have occurred in small protected natural areas where the limited range of represented environmental conditions reduces the applicability of their findings in dissimilar settings. This study investigates a dataset from a large and ecologically diverse representative sample of the entire Appalachian Trail from Georgia to Maine which significantly broadens the relevance of its findings. Furthermore, many previous trail studies have focused on single forms of trail degradation whereas this study which investigates three, which provides a more cohesive analysis and reveals interrelationships between impacts. Findings confirm the broad pertinence of core sustainable trail design principles, specifically the benefits of low trail grades and side-hill alignments, and suggests that landform grade is an important factor which has received little attention in the literature. The study also revealed several methodological improvements and considerations which may be useful to trail scientists and practitioners.
The Influence of Layout on Degradation of the Appalachian Trail

Fletcher Meadema

ACADEMIC ABSTRACT

This research investigates the influence of layout and design on the severity of trail degradation. Previous trail studies have been restricted by relatively small study areas which provide a limited range of environmental conditions and therefore produce findings with limited applicability; this research improves on this limitation by analyzing a representative sample of the Appalachian Trail with significant ecological diversity. Most trail science studies have also focused on a singular form of trail degradation, whereas this study investigates trail soil loss, widening and muddiness, providing a more cohesive analysis and revealing interrelationships between trail degradation processes. ANOVA testing of the mean values of three trail impact indicators for trail transects within several trail layout frameworks confirms the broad relevance of core trail design principles, specifically the sustainability advantages of trails with low grades and side-hill alignments. Findings also reveal the importance of landform grade in determining the susceptibility of trails to degradation and the influence of routing decisions; these relationships have received relatively little attention in the literature. The results also reveal several methodological considerations for trail alignment metrics and trail impact indicators.
Acknowledgements

I would like to thank my advisor, Jeff Marion, for your guidance, support and mentorship, and for your tireless efforts to develop, improve and promote sustainable outdoor recreation. I would also like to thank my other committee members, Jeremy Wimpey and Yang Shao, for sharing your deep knowledge of trails and GIS. I couldn’t have asked for a better committee. Thanks also to the United States Forest Service, the Bureau of Land Management, the National Park Service, the Pacific Crest Trail Association, and the Appalachian Trail Conservancy for funding this research and degree and for protecting wild places and trails. Finally, thanks to Rachel and to my friends and family for your support and patience during my many years in school.
# Table of Contents

Introduction 1

Literature Review 2

*The Influence of Trail Layout on Degradation of the Appalachian Trail* 11

- Introduction 11
- Literature Review 12
- Methods 15
- Results 18
- Discussion 20
- Conclusion 23
- References 23

Appendix A: Trail Assessment Manual 27
List of Figures

Literature Review

Figure 1       Slope Ratio                 4
Figure 2       The Half Rule              5
Figure 3       Trail Slope Alignment Angle 6
Figure 4       Water-Bar Construction     8
Figure 5       Trail Slough and Berms     8
Figure 6       Cross Sectional Area of Soil Loss 10
Figure 7       Sample Locations           16
Figure 8       The Influence of Trail Grade on Soil Loss 18
Figure 9       The Influence of Landform Grade and TSA on Soil Loss 18
Figure 10      The Influence of Landform Grade and TSA on Trail Width 19
Figure 11      The Influence of Rugosity on Trail Width 19
Figure 12      The Influence of Width on CSA  21
List of Tables

Literature Review

Table 1  Guidance from Trail Literature  7
Table 2  Distribution of Transects in Layout Categories  17
Table 3  Mean Maximum Incision Values of Layout Categories  18
Table 4  Distribution of Muddy Transects in Layout Categories  19
Table 5  Mean Width Values of Layout Categories  20
Introduction

Trails provide access to protected natural areas and recreational opportunities for hikers, mountain bikers, equestrians and off highway vehicle (OHV) users. Although their initial construction requires significant environmental alteration (Birchard and Proudman, 2000), sustainably designed trails ultimately protect natural resources by concentrating recreational impacts within narrow trail corridors (Wimpey and Marion, 2010). Consequently, trails are considered an essential infrastructure component in protected natural areas. Recreational traffic and water driven erosion degrade trails, decreasing their utility and requiring costly maintenance and rehabilitation work (Leung and Marion, 1996).

Trail managers are in critical need of better guidance on how to design, construct, and maintain sustainable trails able to support the intended types and amounts of traffic while remaining in good condition.

This thesis describes trail research intended to further the collective understanding of sustainable trail design. The document is structured in three segments: a review of trail literature, a draft journal paper manuscript, and an appendix describing field protocols in detail.
Literature Review

Trail Degradation

Trail treads are vulnerable to loss of vegetation, soil compaction, erosion, muddiness, trail widening, and compositional changes to flora including the introduction of invasive species (Leung and Marion, 1996; Schoenbauer et al., 2006). Erosion is perhaps the most significant of these impacts because natural soil regeneration is extremely slow, soil can not be easily replaced by managers, and once waterborne, soil causes stream sedimentation and degrades aquatic insect and fish habitats (Kidd, Aust, and Copenheaver 2013; Marion et al, 2016; Olive and Marion, 2009). Trail widening greatly increases the areal extent of human impacts and can contribute to erosion and trail drainage problems (Wimpey and Marion, 2010). Trail muddiness can lead to widening and the creation of informal trails as hikers attempt to bypass muddy areas (Leung and Marion, 1996).

Environmental Factors

The severity and scope of trail degradation is strongly influenced by local environmental conditions. Vegetation slows erosion by protecting soils from splash and increasing porosity with roots (Bratton et. al 1979) and vegetation types that are highly resistant to trampling disturbance slow trail widening (Leung and Marion, 1996). Soil texture, reflecting the relative amounts of different particle sizes, influences the ability of soils to withstand erosion, displacement, and compaction. When dry, uniformly fine-grained soils are highly compactible and resistant to erosion; they are prone to muddiness when wet. Coarse-textured soils drain easily but are displaced with little force. An ideal tread substrate has a mixture of grain sizes including larger rocks and gravel to deter displacement and erosion, sand to allow drainage, and fine silts for cohesion (Marion, 2016; Leung and Marion, 2004; Leung and Marion, 1996). Local grade strongly influences soil loss because water flowing on steep slopes has greater velocity giving it more erosive force (Bratton et al, 1979; Dissmeyer and Foster, 1984; Leung and Marion, 1996). Since rainfall and snowmelt are direct agents of erosion, local precipitation levels influence the extent of erosion (Bratton et al, 1979; Leung and Marion 1996).

Trail Design

Trail managers can minimize the influence of some environmental factors by selecting a sustainable trail alignment that will decrease the severity of trail degradation.

Trail Grade

Trail designers or users establish the grade of a trail when they lay out its route. A strong positive relationship exists between soil erosion and high (steep) trail grades (Helgath, 1975; Bratton et al,
Soil loss models suggest that erosional severity becomes significantly greater at grades above 10% (Dissmeyer and Foster, 1984) and trail erosion modeling studies similarly indicate exponential increases in soil loss on grades above 11% (Olive and Marion, 2009). This trend is explained by the increased erosive force of water and increased displacement by boots, wheels, and hooves on slopes (Dissmeyer and Foster, 1984; Leung and Marion, 1996).

Existing trail design books contain inconsistent and unsubstantiated guidance concerning sustainable trail grades. General trail construction texts suggest 10% (Hessselbarth et al 2007), 12% (Basch et. al, 2006), and 20% (Demrow et al, 1998) as maximum sustainable grades. Books specifically for Appalachian Trail design advise 12% (Sommerville, 2003) and 10-15% (Birchard et. al, 2000). Equestrian guides advise 10% (Wood, 2007) and 12% (Hancock et. al, 2007), and OHV and ATV trail literature recommend 12% (Wernex, 1994). Although the bulk of this guidance echoes Olive and Marion’s (2009) modeling findings, none of these books cite empirical evidence or research studies as a basis for their recommendations. Most existing trail design guidance was not derived from or based on trail science research.

Rather than advocating an absolute maximum grade, International Mountain Biking Association (IMBA) guides (Felton et al, 2004; Webber, 2007) and one ATV trail guide (Meyer, 2011) suggest a 10% average grade between significant trail grade reversals that act as tread watershed boundaries. Other books that previously suggested lower maximum trail grades later include allowances of 20% (Felton et al, 2004), 30% (Wernex, 1994) and even 50% (Birchard et. al, 2000) for short distances, particularly when treads have substantial amounts of rock or rockwork steps. Many suggest that such guidance is a rough guideline and that trail grades must be determined in response to local conditions like soil texture, vegetation, rockiness, and climate (Wernex, 1994; Sommerville, 2003; Webber, 2007; Wood, 2007; Meyer, 2011).

**Trail Alignment**

The alignment of a trail in relation to local topography is another significant trail design factor for which comprehensive science-based guidance is relatively lacking. Experienced trail maintainers agree that trails routed directly up slopes, called direct-ascent or fall-line trails, are highly prone to degradation from waterborne erosion. Their close alignment with the natural direction of surface water flow gives them a high propensity to channel water; once incised, even extreme management actions aimed at water drainage are ineffective. Conversely, trails that travel across slopes always have one side-slope lower than the trail tread, which facilitates the removal of water by out-sloping treads and constructing drainage features like water bars or tread grade reversals. These trails, called side-hill trails, shed water easily and require less erosion repair (Marion and Leung, 2004; Marion, 2016). Research has demonstrated that side-hill trails have sustainability advantages in addition to the minimization of soil loss. For instance, steep side-slopes on side-hill trails minimize
trail widening by concentrating traffic on narrow trail treads which can also be easily drained to minimize muddiness (Wimpey and Marion, 2010).

Most trail design guides discourage routing trails directly up slopes and instead favor side-hill alignments (Basch et. al, 2006; Bayfield, 1992; Sommerville, 2003; Felton, 2004; Webber, 2007; Wood, 2007; Meyer, 2011; Birchard, 2000; Schoenbauer, 2007; Hesselbarth, 2007). However, these guides do not offer any specific guidance beyond the aforementioned basic dichotomy and all guidance provided is anecdotal.

**Slope Ratio**

A more descriptive expression of trail alignment commonly used in the trail community is the ratio of the trail grade to the prevailing landform grade, termed slope ratio; it is typically expressed as a number between 0 and 1, although it can be negative to express a downhill grade or expressed as a percentage or fraction. For example, consider a uniform slope with a 25% grade. A side-hill trail across this slope at a 5% grade would have a slope ratio of .2, 20%, or 1/5. A direct-ascent trail routed up this slope at a 20% grade would have a higher slope ratio of .8, 80%, or 4/5.

![Figure 1. Illustrated slope ratios. Left to right .333, .5, and .5 (FELTON 2004).](image)
IMBA has popularized a helpful rule-of-thumb for slope ratio deemed the “Half-Rule.” According to the Half-Rule, a trail’s grade should not exceed one half of the landform grade, yielding a slope ratio of .5 or less. For instance, a trail routed across a 16% slope should not exceed 8% grade. IMBA includes an exception to the Half-Rule when trails are routed across high grades; although the Half -Rule would allow a 20% grade trail routed across a 40% slope, IMBA suggests that no trails should exceed a 15% grade. This guidance prevents direct-ascent trail alignments, but the Half-Rule ratio was not based on empirical evidence or published studies (Felton et al, 2004; Webber, 2007, Marion, 2016). While some trail maintenance guides have adopted the Half-Rule (Hesselbarth, 2007; Meyer, 2011; Wood, 2007), others advocate lower trail slope grade ratios such as one fourth (Basch et. al, 2006; Schoenbauer, 2007).

Figure 2. The Half Rule (Felton 2004).

**Trail Slope Alignment Angle**

Rather than using a slope ratio, trail alignment is sometimes expressed in scientific literature as trail slope alignment (TSA) angle (Leung and Marion, 1996; Leung and Marion, 2004). TSA is calculated as the smallest difference between the compass bearings of the trail’s alignment and the prevailing landform slope (aspect). Side-hill trails have high TSA measurements ranging from 45° to 90°, whereas direct-ascent trails have TSA measurements closer to 0°. Trails with low TSA values travel more directly up slopes and closely parallel the direction of water drainage (Marion, 2016). Consequently, tread incision from soil compaction and displacement produces an incised channel that funnels water, accelerating erosion on slopes and leading to muddiness in flatter areas (Basch et al., 2007; Schoenbauer, 2007; Olive and Marion, 2009; Wimpey and Marion, 2010, Marion, 2016).
Figure 3. Trail slope alignment angle.

Research has demonstrated that TSA is a strong indicator of trail sustainability; high TSA values are strongly linked to reductions in soil loss, muddiness, and tread widening. Regression modeling has yielded predictive equations that suggest that every degree that TSA alignments shift from 90° (side-hill) to 0° (fall-line) contributes 6cm² of additional soil loss, a stronger influence than trail grade (Olive and Marion, 2009). This research also reinforces speculation that the significance of TSA increases as trail grade increases (Leung and Marion, 1996; Olive and Marion, 2009; Marion, 2016). Interestingly, while the negative influence of low TSA values increases with trail grade, the positive influence of high TSA values increases with landform grade (Olive and Marion, 2009).
<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
<th>Pg #s</th>
<th>Max Trail Grade</th>
<th>Avoid Fall Lines</th>
<th>Slope Ratio</th>
<th>TSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basch et al.</td>
<td>Sustainable Mountain Trails Sketchbook</td>
<td>8, 66</td>
<td>8-12%</td>
<td>X</td>
<td>1/4</td>
<td></td>
</tr>
<tr>
<td>Bayfield</td>
<td>Managing the Impacts of Recreation on Vegetation and Soils</td>
<td>17</td>
<td>none</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wernex</td>
<td>Off-highway motorcycle and ATV trails: Guidelines for Design, Construction, Maintenance, and User Satisfaction</td>
<td>14</td>
<td>12%, 30% for short distances</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sommerville</td>
<td>Appalachian Trail Fieldbook: Maintenance and Rehabilitation Guidelines for Volunteers</td>
<td>82</td>
<td>12%</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felton</td>
<td>Trail Solutions: IMBA's Guide to Building Sweet Singletrack</td>
<td>56-66</td>
<td>10% average, 15-20% for short distances</td>
<td>X</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>Webber</td>
<td>Managing Mountain Biking: IMBA's Guide to Providing Great Riding</td>
<td>99-104, 112-120</td>
<td>10%</td>
<td>X</td>
<td>1/2</td>
<td>X</td>
</tr>
<tr>
<td>Wood</td>
<td>Recreational Horse Trails in Rural and Wildland Areas: Design, Construction, and Maintenance</td>
<td>37-41</td>
<td>10%</td>
<td>X</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>Meyer</td>
<td>A Comprehensive Framework for Off-Highway Vehicle Trail Management</td>
<td>3-6, 44</td>
<td>10%</td>
<td>X</td>
<td>1/2</td>
<td>X</td>
</tr>
<tr>
<td>Demrow &amp; Salisbury</td>
<td>The Complete Guide to Trail Building and Maintenance</td>
<td>44</td>
<td>20%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Birchard &amp; Proudman</td>
<td>Appalachian Trail Design, Construction, and Maintenance</td>
<td>48-52</td>
<td>10-15%, 30% or 50% for short distances</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hancock et al</td>
<td>Equestrian Design Guidebook for Trails, Trailheads, and Campgrounds</td>
<td>60-61</td>
<td>12%, 20% for short distances</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schoenbauer</td>
<td>Trail Planning, Design, and Development Guidelines</td>
<td>6.13 - 6.16</td>
<td>1/3 rule</td>
<td>X</td>
<td>1/4 or 1/3</td>
<td></td>
</tr>
<tr>
<td>Hesselbarth et al</td>
<td>(USFS) Trail Construction and Maintenance Notebook</td>
<td>5,12, 17-18</td>
<td>10%</td>
<td>X</td>
<td>1/2</td>
<td></td>
</tr>
</tbody>
</table>
Maintenance Actions

Once a trail has been constructed, trail maintainers combat erosion by manipulating a trail’s cross-sectional shape, drainage features, and tread substrates (Marion and Leung, 2004). Drainage features such as water bars and drainage dips minimize erosion by diverting surface water from the tread. These structures generally consist of an angled ditch backed by an earthen or wooden mound or dam (Hesselbarth, 2007; Mende and Newsome, 2006). Effective implementation of tread drainage features requires design and construction expertise that many trail maintainers lack; an efficacy study in Stirling Range National Park, Australia found that only 13% of water bars diverted water from treads due to consistently improper construction methods (Mende and Newsome 2006).

Managers manipulate the cross-sectional tread shape by out-sloping (most common), in-sloping, and crowning trails to encourage maintenance of sheet flow down slopes rather than allowing water to channel down trails (Dissmeyer and Foster, 1984; Hesselbarth et al, 2007). Over time, traffic on side-hill trails compacts and displaces soil from the center of the tread which produces a raised berm on the lower edge of the trail that inhibits drainage and must be removed. Cut-slopes above side-hill trails deposit soil and debris called slough on the uphill side of the tread, requiring further repair (Hesselbarth, 2007). Whereas berms and slough can be excavated, drainage and repair of incised fall-line trails is difficult or impossible because both side-slopes are above the trail tread channeling water (Hesselbarth 2007; Marion 2016).
Maintainers can slow erosion by hardening treads with rock and other materials. The addition of crushed gravel may not be aesthetically pleasing, but it can be an effective method of creating a highly resistant tread surface, particularly when both fine and coarse particles are included (Marion and Leung, 2004; Marion 2016). Rock steps are constructed to prevent erosion on steeper slopes but no available research has examined their efficacy (Marion 2016). A variety of geosynthetics are also available, including geotextiles, sheet drains, and geocells, and some have been applied on trails to prevent erosion (Hesselbarth et al., 2007). Geosynthetic efficacy research is lacking, and the high cost and artificial nature of these materials discourages their use (Marion and Leung 2004).

**Other Soil Loss Research**

A variety of soil erosion models have been developed in agriculture with applications to forest roads and trails; these describe empirically derived relationships between environmental factors and erosion. Multiple versions of the Universal Soil Loss Equation (USLE), such as the Revised USLE, predict sediment yield by area and time \( \frac{\text{tons of sediment}}{\text{acre-year}} \). These models were developed using data from sediment traps in agricultural and forest settings, and have been applied with success both in these locations and in construction sites. Six factors are included in the basic USLE model: rainfall-runoff erosivity, soil erodibility, slope length, slope steepness, cover-management, and support practice (Renard, et al. 1997).

These models were not developed for application on hiking trails, but they have been used in analyses of erosion on natural-surfaced forest roads and some trails. A comparison of estimates from multiple soil loss models (USLE-Forest, RUSLE2, and the Water Erosion Prediction Project for Forest Roads) to sediment trap data on bladed forest skid trails suggested that although the models were effective at ranking erosion rates from different skid trail treatments, only USLE-Forest and RUSLE2 had satisfactory prediction accuracy and applicability for bladed skid trails (Wade, Bolding, Aust, Lakel, Schilling, 2012). These methods have been applied to trail research but this use is somewhat impractical and not fully validated. For example, one study used USLE-Forest and WEPP to estimate erosion rates on approaches to stream crossings which correlated to downstream changes in macro invertebrate diversity (Kidd et al. 2014).

**Measuring Soil Loss on Trails**

Rather than studying erosion in terms of sediment yield rates, recreation ecology trail researchers measure biophysical indicators which describe trail conditions and degradation. These indicators include binary markers of the presence of problems such as mud-holes, braided trails, and exotic species or measurements such as tread width, maximum and mean tread incision, and cross-sectional area (CSA). CSA is a popular indicator of soil loss; it is calculated from a series of vertical measurements taken from a transect oriented perpendicular to the trail tread at the height of an estimated post construction tread surface. It measures soil loss in a plane at the trail transect,
and can be extrapolated to calculate a total volume of soil lost across a section of trail (Marion, Leung, and Nepal 2006).

**Figure 6.** Illustration of the cross-sectional area method of measuring soil loss.
The Influence of Trail Layout on Degradation of the Appalachian Trail

1. Introduction

Trails provide access to protected natural areas and recreational opportunities for hikers, mountain bikers, and equestrians. Although their initial construction requires significant environmental alteration, sustainably designed trails ultimately protect natural resources by concentrating recreational traffic and impacts within narrow trail corridors (Wimpey and Marion, 2010). Consequently, trails are considered an essential infrastructure component in protected natural areas, and there are an estimated 193,500 miles of trails on federal lands in the United States (American Hiking Society, 2015).

Recreational traffic and natural processes can degrade trails, decreasing their utility and requiring costly maintenance and rehabilitation work (Leung and Marion, 1996). Trail treads are vulnerable to loss of vegetation, soil compaction, erosion, muddiness, trail widening, and compositional changes to flora including the introduction of invasive species (Leung and Marion, 1996; Marion et al., 2016). Water-driven erosion is perhaps the most significant of these impacts because natural soil regeneration is extremely slow, soil cannot be easily replaced by managers, and once waterborne, soil causes stream sedimentation and degrades aquatic insect and fish habitats (Kidd, Aust, and Copenheaver 2013; Marion et al, 2016; Olive and Marion, 2009). Furthermore, unmitigated erosion results in treads with deep ruts or exposed rocks and roots that impair trail travel and exacerbate tread widening and muddiness (Marion et al, 2016, Marion Wimpey 2017). Trail widening from trailside travel greatly increases the areal extent of human impact and can contribute to additional erosion and tread drainage problems (Wimpey and Marion, 2010). Trail muddiness can also lead to widening and the creation of visitor-created trails when hikers attempt to bypass muddy areas (Leung and Marion, 1996).

Although local climate, soils, and vegetation influence the rate and severity of trail degradation, designers can minimize the influence of these factors by selecting sustainable trail alignments relative to topography. Experienced trail professionals agree that steep trails routed directly up slopes, called direct-ascent or fall-line trails, are highly prone to degradation from waterborne erosion and widening. Their close alignment with the natural direction of surface flow promotes channeling water; once incised, it is extremely difficult to drain water off and away from their treads. Conversely, less steep side-hill trails that travel across slopes always have one side-slope lower than the trail tread, which facilitates drainage across or off the trail to the downhill side (Marion and Leung, 2004; Marion, 2016) and inhibits trail widening behavior (Wimpey and Marion, 2010).

Several metrics are used to describe a trail route’s relationship to topography. Trail practitioners most often use Slope Ratio (SR) which is calculated by dividing the landform grade by the trail grade and ranges from 0 to 1. Fall line trails are nearly as steep as their surrounding terrain and
have SR values close to 1, whereas side-hill trails have lower SR values close to 0. Trail researchers typically use Trail Slope Alignment (TSA), a measure of the smallest angle between the trail and the prevailing slope direction which is expressed in degrees and ranges from 0° to 90°. Fall-line trails which closely parallel slope directions have narrow TSA angles close to 0°; side-hill trails have wider TSA angles closer to 90°.

Most trail guidance books advise limiting trail grades and avoiding direct-ascent routes but rarely cite empirical data and research as a basis for their recommendations. The limited geographic scope of past trail studies limits the applicability of their findings in dissimilar settings. Trail managers are in critical need of better guidance on how to design, construct, and maintain sustainable trails able to support the intended types and amounts of traffic while remaining in good condition. This research investigates the influence of trail layout on degradation using an exceptionally large and environmentally diverse Appalachian Trail dataset spanning from Georgia to Maine.

2. Literature Review

2.1 Trail Soil Loss

Soil loss as measured in trail studies is largely caused by water erosion, though wind can remove tread soils in dry climates, and soil can be compacted or displaced downhill or laterally (Marion and Wimpey, 2017). The rate and severity of soil loss is influenced by trail alignment and local environmental conditions. Soil texture, reflecting the relative amounts of different particle sizes, influences the ability of soils to withstand wind and water erosion, displacement, and compaction. When dry, uniformly fine-grained soils are highly compactible and resistant to erosion; coarse-textured soils drain easily but are displaced with little force (Hammitt et al., 2015). An ideal tread substrate has a mixture of grain sizes including larger rocks and gravel to deter displacement and erosion, sand to allow drainage, and fine silts for cohesion (Leung and Marion, 1996; Marion et al., 2016).

Since rainfall and snowmelt mobilize and displace soil, the amount and intensity of precipitation influences the severity of soil loss (Bratton et al., 1979; Leung and Marion, 1996; Tomczyk et al., 2016). Even trampling-resistant grassy vegetation cannot withstand more than low levels of trail traffic, but trailside vegetation limits erosion by protecting soils from splash, blocking and filtering runoff, and increasing soil porosity with roots (Bratton et al., 1979; Dixon et al., 2004). High elevation trails can be more vulnerable to erosion due to the combined effect of high precipitation, wind, unstable soils, and numerous freeze-thaw cycles (Nepal, 2003).

Trail science studies reveal a strong positive relationship between soil erosion and high trail grades (Bratton et al., 1979; Cole, 1983; Fox and Bryan, 2000; Helgath, 1975; Marion and Wimpey, 2017; Nepal, 2003; Olive and Marion, 2009). Several studies have observed exponential increases in soil loss on the steepest grades (Dissmeyer and Foster, 1980; Olive and Marion, 2009). This trend is explained by the increased erosive force of water and increased displacement by boots, wheels, and hooves (Fox and Bryan, 2000; Leung and Marion, 1996).
Direct ascent-trails with TSA values lower than 22° are particularly prone to soil loss (Marion and Wimpey, 2017). Predictive equations from regression modelling suggest that every degree that TSA alignments shift from 90° (side-hill) to 0° (fall-line) contributes 6cm² of additional soil loss (Olive and Marion, 2009). Several studies report that the significance of TSA increases as trail grade increases (Bratton et al., 1979; Leung and Marion, 1996; Marion and Wimpey, 2017; Olive and Marion, 2009).

On side-hill trails managers can configure the cross-sectional tread shape by out-sloping (most common), in-sloping, and crowning trails to encourage maintenance of sheet flow down slopes rather than allowing water to channel down trails. Over time, traffic on side-hill trails compacts and displaces tread substrates and forms a raised berm along the lower edge which contributes to the erosive diversion of water along the tread. The excavation of berms is strenuous yet feasible but drainage and repair of incised fall-line trails is difficult or impossible because both side-slopes are above the tread and channeled water is not easily drained (Hesselbarth et al., 1996; Marion et al., 2016).

Drainage features such as rock or wooden water bars and drainage dips minimize erosion by diverting flowing water from the tread, but the effective application of such features requires side-hill trail designs, construction expertise, and routine maintenance (Hesselbarth et al., 1996; Mende and Newsome, 2006). Despite their variable efficacy, increasing distances to drainage features are linked to higher levels of soil loss (Marion and Wimpey, 2017). The most effective option for diverting water from treads is to temporarily reverse the grade of the trail, forcing all water off the trail and eliminating the need for periodic maintenance. These features are called grade reversals or rolling grade dips (Hesselbarth et al., 1996).

Maintainers can also slow erosion by hardening treads with rock and other materials. The addition of imported gravel or crushed native stone may seem unnatural but can be an effective practice to create highly resistant treads, particularly when both fine and coarse particles are combined (Marion et al., 2016). Loose gravel applied on steep trail sections is often transported down-slope, requiring labor intensive re-application and maintenance (Marion and Wimpey, 2017; Olive and Marion, 2009). Rock steps can be constructed to prevent erosion on steeper slopes but no available research has examined their long-term efficacy (Marion et al., 2016). A variety of geosynthetics are also available, including geotextiles, sheet drains, and geo-cells, and some have been applied on trails to prevent erosion (Hesselbarth et al., 1996). Geosynthetic research is lacking, and the high cost and artificial nature of these materials discourages their use (Marion and Leung, 2004).

Type and amount of trail use have also been shown to influence soil loss, though most studies report their influence is less than that associated with sustainable trail designs (Cole, 1991). Several studies have observed rapid soil displacement on equestrian trails relative to hiking and mountain biking trails (Bratton et al., 1979; Leung and Marion, 1999; Olive and Marion, 2009). High levels of use, particularly during wet periods, can accelerate trail erosion (Farrell and Marion, 2001; Nepal, 2003).
2.2 Trail Muddiness

While studies suggest that soil loss is primarily caused by moving water, trail muddiness is caused by poor drainage and water retention. Although a common problem in many trail systems during wet seasons (Cole 1983, Leung and Marion 1999; Nepal 2003) little research has been focused on modeling the factors that influence trail muddiness. Trails routed through flat areas are prone to muddiness because it is difficult or impossible to drain water from their incised treads (Cole, 1983; Tomczyk et al., 2017). Trails in areas with high water tables or on soil types with substantial organic content that retain water often become muddy quagmires (Bratton et al., 1979; Cole, 1991; Leung and Marion, 1999). Mud-holes form often in flatter valley bottoms in areas of poor drainage or near seeps and springs (Bratton et al., 1979; Leung and Marion, 1999; Nepal, 2003), although muddiness can be common on side-hill trails and on ridgetops as well (Bratton et al., 1979; Leung and Marion, 1999). Flat “contour-aligned” side hill trails become muddy when infrequent maintenance allows berms to form and water-bars to clog, causing water retention and muddiness (Hesselbarth et al., 1996). Regardless of location, trail maintainers frequently harden persistently muddy trail segments with rock, puncheon, geosynthetics or elevated bog bridging; when possible, relocating such segments to side-hill alignments with sloping trail grades can be a more effective long-term solution (Hesselbarth et al., 1996; Steinholtz and Vachowski, 2001).

2.3 Trail Widening

Unlike soil loss and muddiness, which are driven by water, trail widening is caused by visitors when they move laterally and trample areas adjacent to the intended tread (Cole, 1991; Wimpey and Marion, 2010). Consequently, variations in numbers and types of trail users and their behaviors strongly influence trail width. For example, high use trails are prone to widening due to visitors moving laterally to pass or allow passing and side-by-side travel (Marion and Olive, 2006; Nepal, 2003; Svajda et al., 2016; Tomczyk et al., 2017; Wimpey and Marion, 2010). Motorized vehicles and equestrians have a functional need for wider trails but the greater speeds and distances traveled and greater ground pressures and soil displacement caused by tires and hooves can also contribute to trail widening (Marion and Olive, 2006; Svajda et al., 2016; Tomczyk et al., 2017).

Topography and trail routing also significantly influence trail width. Trails built through flat areas are prone to widening due to the ease of off trail travel and the higher likelihood of muddiness (Wimpey and Marion, 2010). Unmitigated degradation on poorly routed trails can prompt visitor behaviors that contribute to trail widening; hikers meandering laterally over eroded rocky and root-covered treads in search of the best footing often pioneer smoother areas adjacent to the degraded treads (Leung and Marion, 1999; Tomczyk et al., 2016; Wimpey and Marion, 2010). Similarly, trail users frequently sidestep wet and muddy trail sections, creating multiple treads and wide mud-holes (Bayfield, 1973; Leung and Marion, 1999; Tomczyk et al., 2017). In contrast, the steeper side-slopes and terrain adjacent to side-hill trails acts to concentrate traffic and inhibit widening (Bayfield, 1973; Wimpey and Marion, 2010).

Whereas degraded trail conditions motivate visitors to travel adjacent to the intended tread, off-trail attributes can aid in keeping trails narrow. Dense vegetation can concentrate and center traffic when present and maintainers can strengthen or weaken this effect when conducting trimming (Bayfield, 1973; Bright, 1986; Hesselbarth et al., 1996; Tomczyk et al., 2017) Both natural and intentionally placed trailside rocks and woody debris can effectively center traffic on smoother
trail surfaces (Bayfield, 1973). Constructed trailside barriers like trail borders, scree walls, and fencing physically obstruct traffic or simply serve as visual cues and both are effective means of concentrating use (Park et al., 2008; Svajda et al., 2016; Tomczyk et al., 2017; Wimpey and Marion, 2010). Durable trailside grasses prevent widening through resistance and resilience to trampling (Tomczyk and Ewertowski, 2011; Tomczyk et al., 2017). However, trails through wet alpine meadows often have muddiness-related widening and multiple treads (Nepal, 2003).

3. Methods

3.1 Study Area

The Appalachian Trail is the nation’s first and most popular National Scenic Trail and the world’s longest pedestrian only footpath. It is marked with white blazes for 2,190 miles through 14 states from Springer Mountain, Georgia to Mount Katahdin in Maine. An estimated 3 million people visit the trail annually and the number of completed and attempted end-to-end “thru-hikes” has been steadily rising for many years. The AT was originally proposed in 1921 by regional planner Benton MacKaye to create a corridor of protected natural landscapes and recreation opportunities accessible to major population centers along the Eastern United States. Construction began in Harriman and Bear Mountain State Parks in 1923 and a continuous footpath was established by 1937. Final federal land acquisition to fully protect the AT corridor was completed in 2014 and today over 280,000 acres of protected trailside land act as a biodiverse greenway home to many rare and endangered species.

The National Scenic Trails Act of 1968 designated the AT a unit of the National Park Service, which employs a unique cooperative-management partnership between many land management agencies and volunteer trail clubs to manage the trail. The primary partner of the NPS is the non-profit Appalachian Trail Conservancy which oversees a variety of trail-wide conservation efforts and coordinates and supports 31 volunteer trail maintenance clubs. Over one thousand miles of the trail is located on national forest land, and the US Forest Service is an active trail partner. Agencies that oversee the numerous state parks, game lands, and localities through which the trail passes are also involved in its management.

3.2 Sampling and Measurement Procedures

The Generalized Random Tesselation Stratified (GRTS) approach was used to sample trail segments and points where transects were placed for assessing trail conditions (Kincaid and Olsen 2011). The GRTS software generated a spatially balanced sample of the entire Appalachian Trail consisting of 63 5km segments (195.3 miles, ~9% of the trail’s total length) each containing 50 trail points (3150 total). (Stevens Jr and Olsen, 2004). The northern-most 21 segments between Connecticut and Maine were surveyed in the summer of 2015. The southern-most 21 segments between Georgia and southwest Virginia were surveyed in the summer of 2016, and the remaining 21 segments between Virginia and New York were surveyed in the summer of 2017. A special mud-hole study was added during the 2016 and 2017 field seasons whereby muddy trail segments were purposively surveyed to provide additional data for this rare form of trail degradation.

Sample locations were loaded onto a Trimble Geo7X GPS unit used to navigate to the sample points and record a precise averaged GPS point at the survey location. All data was recorded on tablets using survey forms created in Qualtrics© in 2015 and Fulcrum© in 2016 and 2017.
At each sample point a temporary trail transect was established perpendicular to the trail tread. Metal stakes were inserted into the ground at the most pronounced outer boundary of visually obvious human disturbance created by trail use. A flexible measuring tape was affixed tautly between the two stakes at the height judged to be the post-construction pre-use tread surface. If protruding rocks or roots obstructed the tape at the desired height it was raised in 5cm increments on both stakes until clear of the barrier and the offset distance was recorded and subtracted from measurements. The distance between the metal stakes was measured with a measuring tape and recorded to the nearest half centimeter as tread width. Maximum incision was measured as the largest perpendicular distance between the transect tape and the tread surface. The tread composition was estimated along a 20cm band centered on the trail transect and recorded to the nearest 5% in the following categories: soil, litter, vegetation, rock, mud, gravel, roots, water, wood and other. A full description of the field measurement protocols may be found in Appendix A.

The trail grade at the transect was measured to the nearest degree using a clinometer sighted between one field crew member on the transect and another on the trail 3m uphill. Similarly, the landform grade was measured between the transect and a point 3m uphill along the fall line. Trail slope alignment was measured as the smallest difference in compass bearing between the trail and the prevailing landform aspect. The soil texture was determined by feel and a ribbon test at the beginning of each segment and when the survey crew observed changes in soil appearance thereafter. The tread type was recorded from the following categories: soil/organic muck, bedrock, rock (cobble to boulder), bog bridge, boardwalk, dirt or gravel road, paved road, rock step/rock work, sidewalk, and stream. Oblique and overhead photographs were taken of each transect using tablet cameras.
3.3 Analysis

Data was uploaded from tablets to the Fulcrum online server and then exported into Excel 2016 and then JMP Pro 13.0.0. Trail and landform grades were converted from degree slope to percent slope for relevance to the trail community. Analyses of soil loss and widening included only trail transects with the soil/organic muck tread type where it was appropriate to record a soil texture, maximum incision, and tread width. Transects at local high points were also excluded because trail grades were measured below the transect. Based on these criteria 510 transects were excluded and 2639 were retained. Statistical tests were performed in JMP 13.0.0 to investigate the relationships between trail layout metrics and trail degradation indicators.

Several trail layout groupings were evaluated based on previous studies and professional judgement. Trail grade was categorized based on groupings from a recent trail soil loss study (Marion and Wimpey, 2017), which were also applied to landform grade and combined to create a framework which expresses overall layout; within landform grade categories, higher trail grade categories indicate more direct-ascent routes with higher slope ratios and lower TSA values (Table 2). For other analyses, transects were categorized using a system that differentiated the highest and lowest TSA values and categorized landform grade into three classes for soil loss analyses and two for widening.

To investigate the influence of trail layout on soil loss, one-way ANOVA was performed comparing the mean values of maximum incision within trail grade categories (see Figure 2). Full factorial two-way ANOVA and a post-hoc Student’s T test was performed to compare the mean values of maximum incision within TSA and landform grade categories. Finally, an ANOVA test was performed to compare the mean values of maximum incision within the combined trail and landform grade categories.

Similar analyses were performed to explore the effects of trail layout on widening. One-way ANOVA was performed comparing the values of trail width to combined landform and trail grade categories and a full factorial two-way ANOVA was performed comparing the values of tread width within TSA and landform grade categories. One-way ANOVA was performed comparing the mean trail width values within different tread rugosity categories to investigate the influence of tread roughness on trail width. Finally, mean trail width categories were calculated for each segment to investigate the relationships between widening, use intensity and trail construction and history.

To investigate trail muddiness, summary statistics were generated for trail transects for which 20% or greater of the tread substrate was mud or water and for purposively surveyed mud holes.

<table>
<thead>
<tr>
<th>Landform Grade</th>
<th>0-2%</th>
<th>2-10%</th>
<th>10-20%</th>
<th>20+%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trail Grade</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2%</td>
<td>132</td>
<td>189</td>
<td>98</td>
<td>88</td>
<td>507</td>
</tr>
<tr>
<td>5.0%</td>
<td>2-10%</td>
<td>381</td>
<td>316</td>
<td>372</td>
<td>1069</td>
</tr>
<tr>
<td>14.4%</td>
<td>10-20%</td>
<td>334</td>
<td>472</td>
<td>806</td>
<td>30.5%</td>
</tr>
<tr>
<td>12.7%</td>
<td>20+%</td>
<td>257</td>
<td>257</td>
<td>514</td>
<td>9.7%</td>
</tr>
<tr>
<td>9.7%</td>
<td><strong>Total</strong></td>
<td>132</td>
<td>570</td>
<td>748</td>
<td>1189</td>
</tr>
<tr>
<td>5.0%</td>
<td></td>
<td>21.6%</td>
<td>28.3%</td>
<td>45.1%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 2 Distribution of transects within trail layout groupings. Values are sample size (N) and percent of cases (%).
Summary statistics were also calculated for boardwalk and bog/bridge sections to investigate the frequency of intensive mud management actions.

4. Results

4.1 Trail Soil Loss

One-way ANOVA testing confirmed that the severity of soil loss varies significantly with trail grade ($F = 21.3, p < .0001, df = 3$), with a post-hoc Student’s T test revealing significant increases between each category of trail grade (Figure 8). A one-way ANOVA test examining the influence of combined trail and landform grade layout categories on mean maximum incision found significant differences between groups ($F = 8.1, p < .0001, df = 9$), and a post-hoc Student’s T test identified the greatest soil loss occurring on transects with trail and landform grades in excess of 20% (Table 3).

Another two-way ANOVA test revealed that soil loss values vary significantly with both landform grade ($F = 24.8, p < .0001, df = 2$) and TSA ($F = 8.0, p < .0001, df = 4$), with a significant interaction between the two ($F = 2.3, p = .0169, df = 8$). In sloping terrain above 10%, maximum incision values increase as TSA values decrease (Figure 9), with the greatest incision values occurring on fall-line trails on landform grades in excess of 20%.

Table 3 Maximum incision values increase with both trail grade and landform grade. The most incised trails are fall-line trails which have high trail grades.

<table>
<thead>
<tr>
<th>Landform Grade</th>
<th>0-2%</th>
<th>2-10%</th>
<th>10-20%</th>
<th>20+%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trail Grade</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2%</td>
<td>5.0</td>
<td>6.3</td>
<td>5.2</td>
<td>8.6</td>
</tr>
<tr>
<td>2-10%</td>
<td>5.8</td>
<td>6.6</td>
<td>6.6</td>
<td>6.9</td>
</tr>
<tr>
<td>10-20%</td>
<td>7.4</td>
<td>6.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20+%</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8 Mean maximum tread incision values are significantly different across trail grade categories. Soil loss increases with increasing trail grade.

Figure 9 Mean maximum incision values are significantly higher in lower TSA categories, and this relationship is stronger in steeper terrain. Note the inverse relationship between TSA and trail grade.
4.2 Trail Muddines
There were 70 muddy trail transects within the random sample, 2.3% of total, and an additional 40 purposively surveyed muddy areas. The random sample also included 34 muddy locations where trail maintainers had installed bog bridging (18 transects) and boardwalks (16 transects), cumulatively totaling 1.1% of the sample. The mean trail grade of the 110 random and purposively sampled muddy transects was 7.9% and the mean landform grade was 19.9%. These values are similar to the overall dataset for which the mean trail grade is 9.4% and the mean landform grade is 23.1%. The relative distribution of transects within trail and landform grade categories for muddy transects (Table 3) also roughly emulates the entire sample (Table 1). The bog bridging and boardwalks were found in flatter terrain, with an average landform grade of 4.5%.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Relative distribution of muddy transects within combined trail and landform grade categories.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trail Grade</td>
<td>Landform Grade</td>
</tr>
<tr>
<td>0-2%</td>
<td>2</td>
</tr>
<tr>
<td>2-10%</td>
<td>16</td>
</tr>
<tr>
<td>10-20%</td>
<td>16</td>
</tr>
<tr>
<td>20+</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Figure 10</th>
<th>In flat terrain, TSA has little bearing on trail width. In sloping terrain, side-hill trails stay narrow and fall-line trails become extremely wide.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 11</td>
<td>Treads become rougher when soil loss exposes rocks and roots. Rougher treads become wide because hikers often travel beside them for smoother footing.</td>
</tr>
</tbody>
</table>

4.3 Trail Widening
Two-way ANOVA testing revealed significant differences (F = 8.8, p = .003, df = 1) between mean trail width values within different landform grade categories (Figure 10), but not between different TSA categories (F = 1.9, p = .106, df = 4). However, the interaction effect between TSA and Landform Grade was significant (F = 3.7, p = .0056, df = 4). TSA values have little influence on maximum incision values in flat terrain (<15%), but have a strong inverse relationship with
maximum incision on slopes above 15%. A one-way ANOVA test comparing mean tread width within combined trail and landform grade categories (Table 5) found significant differences between categories (F = 3.9, p < .0001, df = 9). Another one-way ANOVA test found significant tread width differences across different tread rugosity categories (F = 87.3, p < .0001, df = 2). Trails with rougher treads were significantly wider than smoother trails (Figure 11). Average tread width in the random sample is 64.1 cm (n = 2,639), and average tread width for random and purposively surveyed muddy transect is 137.6 cm.

Table 5 Tread width values within different trail and landform grade categories are significantly different. Steep, fall-line trails with landform and trail grades exceeding 20% are the widest trails due to erosion induced roughness. Side-hill alignments in steep terrain effectively inhibit widening.

<table>
<thead>
<tr>
<th>Landform Grade</th>
<th>0-2%</th>
<th>2-10%</th>
<th>10-20%</th>
<th>20+%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trail Grade</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2%</td>
<td>62.0</td>
<td>64.5</td>
<td>66.2</td>
<td>66.2</td>
</tr>
<tr>
<td>2-10%</td>
<td>67.8</td>
<td>62.6</td>
<td>58.1</td>
<td></td>
</tr>
<tr>
<td>10-20%</td>
<td>65.8</td>
<td>61.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20+%</td>
<td>69.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean Tread Width (cm) Students T Test Groups (ABCD); values with the same letter are not significantly different.

5. Discussion
5.1 Soil Loss
The findings of this study reinforce an existing consensus that steep trails are prone to severe soil loss (Bratton et al., 1979; Cole, 1983; Fox and Bryan, 2000; Helgath, 1975; Marion and Wimpey, 2017; Nepal, 2003; Olive and Marion, 2009). Maximum incision values increase with trail grade across the diverse AT dataset, and the steepest trail segments are the most severely incised. It is critical that grades are limited during future trail construction and that existing steep sections are actively monitored and maintained or relocated when feasible.

The results suggest that TSA is an important design factor and that it’s consequence increases as landform grade increases. This is a slight departure from other studies which have reported that the importance of TSA increases as trail grade increases (Bratton et al., 1979; Leung and Marion, 1996; Marion and Wimpey, 2017; Olive and Marion, 2009). However, this research reveals several benefits of expressing layout by pairing landform grade with either trail grade or TSA.

Trail grade and TSA are managerially established in a single layout decision which is constrained by landform grade, an environmental attribute which can be intentionally selected during siting but is not typically altered beyond trail treads. Furthermore, TSA and trail grade have an inherent relationship which makes any guidance coupling them somewhat redundant. When comparing trail segments on equivalent slopes, direct-ascent routes with low TSA values are intrinsically steeper than side hill trails; decreases in TSA equate to increases in trail grade.

Maximum incision values are consistently minimal in low landform grade areas where trail grades are naturally limited regardless of alignment but they soar on steep slopes, especially when trails are routed directly uphill. Consequently, the inverse relationship between maximum incision and
TSA values is stronger as landform grade increases; maximizing TSA has tremendous consequence in sloping terrain but little meaning in flatter areas. Trail designers can operationalize the importance of landform grade during initial trail siting; expensive side-hill construction is necessary to inhibit soil loss in steep terrain but construction costs can be minimized while still achieving sustainability goals by routing trails through less steep areas when available.

The impact indicator in many trail soil loss studies has been cross sectional area (CSA) of soil loss, a volumetric assessment measured and calculated via a series of vertical measures taken from a trail transect (Cole, 1991; Marion and Wimpey, 2017; Olive and Marion, 2009; Svajda et al., 2016; Tomczyk et al., 2016). These studies did not report that because CSA measurements reflect the total volume of soil loss they can be heavily influenced by trail widening in addition to soil loss. Future trail researchers communicating soil loss with CSA values should at minimum caution readers of the misleading relationship with width. Maximum incision was selected as the indicator for soil loss in this study because it is not confounded by widening.

Another benefit of maximum incision over CSA for research and monitoring is that it is substantially less time-consuming to measure. Although less appropriate for this analysis which sought to consider erosion separately from widening, CSA could be a valuable indicator for simultaneously evaluating both forms of degradation.

5.2 Trail Muddiness

In contrast to a study which reported that muddiness is the most common form of trail degradation in the Great Smoky Mountains National Park (Leung and Marion 1999), muddiness is relatively rare problem in this Appalachian Trail dataset. Only 2.3% of transects were muddy, and only 40 additional mud-holes were purposively surveyed.

There are several potential explanations for this finding; first among these is the high level of maintenance on the AT. Maintainers resolve muddiness by improving drainage, elevating treads, and relocating trails. The random sample included 18 transects on bog bridging and 16 transects on boardwalks, cumulatively totaling 1.1% of the sample, which suggests that AT trail maintainers
actively fix mud holes even when the solutions are highly labor intensive and expensive. Another potential explanation is the timing of the study’s field season during the drier summer months of June and July; had the surveys occurred during the wetter spring season, more trail segments would have been muddy.

More surprising is the relatively large number of muddy transects in sloping terrain and on graded sections of trail in contrast to other studies that found mud mostly in flatter areas (Cole, 1983; Tomczyk et al., 2017). This could once again be caused by the timing of field surveys; surveys that occurred soon after rain could have erroneously reported “muddy” conditions intended to indicate chronic mudiness. It could also be a result of a limited amount of flat terrain present in the sample; the relative number of muddy transects in landform and trail grade categories are similar to those in the overall dataset. However, mud-holes do occur in sloping terrain when trails incise and drainage features fail and retain water. Maintainers may be less likely to employ intensive construction remedies in these areas where mud is less persistent and logistics are more challenging, which could be anecdotally supported by the relative flatness of boardwalk and bog bridging transects. Future studies may consider the temporal nature of trail muddiness when planning data collection and observe mud-holes at specific or multiple times.

5.3 Trail Widening

The findings of this study supplement former conclusions suggesting that trail conditions related to routing decisions can influence hiker behavior and affect the severity of widening. The widest transects were observed on steep direct-ascent trails where hikers select smooth footing adjacent to eroded rocky and root-covered treads. The strong positive relationship between tread rugosity and width reinforces this explanation. Widening on steep trail segments is particularly problematic because it increases the areal extent of soil exposure on slopes vulnerable to erosion and broadens the catchment size of trail watersheds. Avoidance behavior also drives trail widening in muddy trail sections; the mean tread width for the random and purposively surveyed muddy transects is 137.6 cm (n=110), more than twice the mean for the entire dataset, 64.1 cm (n=2639).

Conversely, sustainable side-hill trails discourage widening behaviors. The narrowest trail transects were observed on side-hill trails in steep terrain where precipitous drop-offs concentrate traffic on the center of treads. Although this is an effective technique to inhibit widening in sloping terrain, routing decisions have little effect on widening in flatter terrain where off-trail travel is relatively easy regardless of alignment, further indicating that landform grade influences the magnitude of routing decisions. Unlike other research, this study did not observe extreme widening in flat terrain, perhaps due to the relative rarity of level landscapes, effective maintenance of muddy trail segments, and coincidental lower use in flat terrain.

Consideration of the mean trail widths for each 5km segment reveal some limitations of the dataset. Several segments with exceptionally large average widths contain attractive features which draw substantially larger numbers of hikers. Although this anecdotally reveals the powerful influence of use level, no data exists which quantifies amount of use comparably across the AT. Additionally, the three segments with the highest average width have sections routed along old woods roads, some of which can be accessed by vehicles for emergency or maintenance purposes. Although wide, these segments are their constructed and intended width. One widening study overcame this limitation by evaluating the difference between intended and assessed trail width.
6. Conclusions
The large scale and diversity of conditions represented in the AT dataset affirm the broad pertinence of core trail design principles. These findings are highly relevant for trail layout and can also be applied to identify poorly routed segments and prioritize management efforts on existing trail systems. Severe soil loss is likely on steep trail sections particularly when fall-line layouts make water diversion an impossibility. Soil loss exposes roots and rocks which encourages off-trail travel and drives widening. Trail muddiness can be largely avoided in sloping terrain, but unchecked degradation and precipitation can still cause muddy conditions. Particularly in areas with high landform grades, side-hill trail designs hinder degradation because they have low grades, are easily drained, and concentrate traffic. Although side-hill layouts do largely inhibit trail degradation, regular maintenance of drainage features is necessary for long term trail sustainability. More research is needed to evaluate the efficacy of various drainage features, particularly grade reversals, to withstand degradation over time without maintenance.

Several methodological considerations stemming from this analysis could benefit future trail scientists and practitioners. First, researchers focused on trail soil loss should be wary of the powerful influence of trail width on CSA measurements and may consider maximum incision a more appropriate indicator. Secondly, researchers should seek to fully understand the geometric relationships between landform grade, trail grade, and TSA before using these metrics to develop analysis frameworks and issue guidance and may consider pairing trail grade or TSA values with landform grade to fully articulate layouts. Trail designers should consider landform grade in initial trail siting, and remember that the powerful influence that their routing decisions exert on the rate and severity of degradation on slopes is much weaker in flat terrain.

Some relational analyses remain limited by the lack of available data from several potentially influential factors. These include trail age, maintenance ethos and intensity, level of use, and environmental characteristics (e.g., precipitation). Such data are often unavailable in trail degradation studies, pointing to the need for further investigations that employ experimental designs where such factors can be manipulated and included.

7. Works Cited


Appendix A: Trail Assessment Manual
Appalachian National Scenic Trail

(version 5/12/2017)¹

This manual describes procedures for conducting an assessment of resource conditions on the Appalachian Trail treadway. These procedures are designed so that they can be replicated, allowing future reassessments for monitoring trail conditions over time. A number of indicators are included to characterize factors expected to influence trail conditions or assess trail design attributes and sustainability. The A.T. tread will be evaluated at selected sample points located within five kilometer sampled segments of the A.T. A spatially distributed GRTS sampling design was applied to determine the locations of the sampled segments and within each, 50 sample points where transects will be located.

Trail conditions will be characterized from measurements taken at the sample point transect locations. Measurements will document the trail’s width, depth, substrate, slope, alignment and other characteristics. These procedures take several minutes to apply at each sample point. Data is summarized through statistical analyses to characterize resource conditions for each A.T. trail segment and for the entire trail system.

Assessments should be taken near the middle or end of the visitor use season but before leaf fall (e.g., June-August). Site conditions generally recover during the fall/winter/spring periods of lower visitation and reflect rapid impact during early (spring) season use. Site conditions are more stable during the summer months and reflect the resource impacts of that year’s visitation. Subsequent assessments, if conducted, should be completed as close in timing to the original year’s measures as possible. Generally monitoring should be replicated at about 5-10 year intervals, unless conditions are changing rapidly.
Materials  (Check before leaving for the field)
☐ Day pack w/x-tra clothing, rain gear, lunch/snacks, water, water filter, hat, sunscreen, tick repellent, first aid kit, phones, wallets, car key, fanny pack, trash bags to cover packs in rain, other?
☐ A.T. topographic maps
☐ Both tablets w/charged battery plus power banks and connector cords, gallon trash bags for rain, umbrella
☐ Trimble GeoXT GPS w/charged and spare battery, stylus, and data dictionary. Loaded with A.T. corridor, treadmill, and the Informal Trail data dictionary.
☐ Garmin 64 GPS unit w/charged & spare batteries loaded with the A.T. study segment endpoints and sample (transect) points
☐ This manual on waterproof paper
☐ Flexible transect line tape measure in centimeters (10 m retractable)
☐ Tape measure for CSA depths in centimeters (3.5m retractable)
☐ Small notebook and pens
☐ Stakes (2) and mini-hammer
☐ Metal binder clips (4+) to attach tape to stakes
☐ Compass/clinometer combo
☐ Pin flags and washers with flagging tape to mark transect locations, flag carrier
☐ Scrapers used to dig soil samples
☐ Digital camera for campsite photos or staff working photos

Point Sampling Procedures

Trail Segment Info: This will be collected later via e-mail and phone contacts to local A.T. trail club members responsible for the measured sections. Collect and record any information that is known about the trail segment’s history, particularly its original construction date, relocation segments and dates, past uses, type and amount of maintenance, history of use, etc. These data need to be spatially documented, particularly the age of the trail and of all relocations or major reconstruction work. This can be recorded on separate paper if a knowledgeable trail club member is present.

Use Level (UL): Also collected at a later date unless a trail club member is present. Record an estimate of the amount of use the trail receives from the most knowledgeable trail club member or agency staff. Work with them to quantify use levels on an annual basis (e.g., low use: about 100 users/wk for the 12 wk use season, about 30 users/wk for the 20 wk shoulder season, about 10 users/wk for the 20 wk off-season = about 2000 users/yr). Be sure that the use characteristics are
relatively uniform over the entire 5k trail segment. Trails may have substantial changes in the amount of use over their length. For example, a road may intersect the A.T., significantly altering use levels. In these instances where substantial changes in the type and/or amount of use occur, the trail should be split in two or more segments with use characterized for each segment. This practice will facilitate the subsequent characterization of trail use. This can be recorded in the Segment form on the iPad or on separate paper.

**Trail Name:** Record a trail segment name based on an included geographic feature.

**Surveyors:** Record initials for the names of the trail survey crew.

**Date:** Record the date (mm/dd/yr) the trail was surveyed.

**Inventory Indicators**

Consult the fieldwork planning information to determine the location of the next trail section to be measured, and the location of the best parking location to access the segment. Use a car GPS and tablet or phone maps to navigate there (if you need paper maps purchase and keep receipts). Recharge any devices not fully charged while driving. Park the car in the safest location possible, take all valuables that you can with you, hiding the rest under clothing in obscure locations, lock all doors/close all windows, leave nothing interesting or valuable “in view.” Ensure that you have all field gear (fully charged with back-up batteries and cords), clothing, rain gear, food, and water before departing the car – double-check this before you leave.

Field staff will operate in two groups, the Trimble operator and the Transect crew. The Trimble operator is generally out front and will use the Garmin GPS in proximity alarm mode to navigate to each trail transect location. When the alarm goes off stop immediately and place wire pin flags on either side of the trail to mark the transect, then record an averaged waypoint precisely at the center of the transect and trail with 50+ points, labelled with the Section and transect numbers (e.g., 2115, Section 21, Transect 15). Do not under any circumstance subjectively “adjust” or move the transect point when the alarm goes off.

The Transect crew will also use a Garmin GPS in proximity mode to navigate to the transects. Sometimes the Garmin operator will be off mapping informal trails or measuring recreation sites and get behind the Transect crew. When this happens the Transect crew will locate and measure the transects, leaving behind two flags indicating the transects and one flag for the Upper Trail Watershed Boundary (UTWB) location for the Trimble operator to find, who will collect the flags after recording averaged waypoints.

Assess A.T. tread conditions at every sample point – no rejections are permitted even if a sample point occurs in a creek or on a road or sidewalk. We have made this decision so that the data
accurately characterize the entire A.T. treadway. If an indicator cannot be assessed, e.g., is “Not Applicable,” record a “-1”. All data will be entered into a tablet computer (Apple iPad and Google Nexus 9). Field forms have been created for these using the Fulcrum software, open these and proceed with data entry.

1) **Trail Segment/Transect:** Record a combined trail segment and transect number (4 digits). Ensure that a waypoint was recorded for each transect point.

2) **Soil Depth (MSD):** Hammer the transect stakes into the ground in off-trail areas in the vicinity of the transect and use a tape measure to determine the typical or mean soil depth to rock: 1=0, bedrock or scree field, 2=1-10 cm, 3=>10 cm. Omit if CSA is -1.

3) **Upslope Trail Grade (TG):** The two field staff should position themselves at the transect and about 3m (10 ft) in an uphill direction on the trail from the transect. Use the clinometer to determine the grade by sighting and aligning the horizontal line inside the clinometer with a spot on the opposite person at the same height as the first person's eyes. Note and record the nearest degree (left-side scale, record as a positive value). If at a local high point (everything within 3m is lower, record a neg. grade value).

4) **Landform Grade (LG):** Place the clinometer on a metal transect boundary stake and orient the stake to match the upslope grade along the fall line beginning above any “cut” slope and extending up-hill three meters. Your objective is to measure the prevailing landform slope in the vicinity of the transect. Look in the clinometer side window and record the nearest degree (positive value) off the visible scale. If at a local high point (everything within 3m is lower, record a neg. grade value).

5-6) **Trail Slope Alignment Angle (TSA):** Looking directly uphill from the sample point, identify and project the fall-line across the A.T. Identify the fall line by thinking about where you would need to pour a bucket of water such that the water would run downhill and intercept the middle of the transect. Ignore the influence of adjacent large rocks and focus on averaged water movement over the uphill landscape. Chose the direction along the A.T. that makes an acute angle (<90°) with the fall line. Sight the peephole compass along the A.T. in the acute angle direction (3m segment) and record as “Trail” the compass azimuth. Repeat to assess and record the azimuth of the fall line as “Fall Line”. The Trail Slope Alignment angle is calculated by subtracting the smaller from the larger azimuth (computed by the tablet) – ensure that it is <90°. If at a local high point (everything within 3m
Soil Texture by Feel

Start: Place soil in palm of hand. Add water drop-wise and knead the soil into a smooth and plastic consistency, like moist putty. Does the soil remain in a ball when squeezed?

Yes

Add more water

Is the soil too dry?

No

Add dry soil

Is the soil too wet?

No

Yes

Sand

Place ball of soil between thumb and forefinger, gently pushing the soil between with the thumb, squeezing it upward into a ribbon. Form a ribbon of uniform thickness and width. Allow ribbon to emerge and extend over the forefinger, breaking from its own weight. Does the soil form a ribbon?

Yes

Loamy Sand

What kind of ribbon does it form?

Moisten a pinch of soil in palm and rub with forefinger

Does it feel very gritty?

Yes

Forms a weak ribbon less than 1" before breaking

LOAM

Sandy Loam

4

Forms a ribbon 1-2" before breaking

CLAY LOAM

Sandy Clay Loam

5

Forms a ribbon 2" or longer before breaking

CLAY

Sandy Clay

6

Silty Clay Loam

7

Silty Clay

8

Sandy Loam

9

Loam

10

Silt Loam

Note: Include comments for questionable data: Q1: fall line, Q2: UTWB, Q3: CSA, Q4: ?

Record a classification:

1 - Sandy Clay
2 - Clay
3 - Silty Clay
4 - Sandy Clay Loam
5 - Clay Loam
6 - Silty Clay Loam
7 - Sandy Loam
8 - Loam
9 - Silt Loam

7) Soil Texture (TX): Use the scraper to remove any thin (<1 cm) of organic soil near the center of the tread. Then excavate soil about the size of a golf ball (4 cm, 1.5 in). Follow the field method described below to describe soil texture at the sample point. This assessment should be done at the start of the trail segment (have some water to use and rinse your hands with). At the following transects you can often check the texture without wetting, but repeat the full method if it appears to have changed.
10 - Black Organic Soil
11 - Rock, gravel, pavement, boardwalk

) **Erosion/Deposition (ED):** Characterize general soil movement at the transect (see Figure):
a) Erosion Zone – a sloping area that could yield soil (soil loss may not be visually evident),
b) Deposition Zone – at the foot of a slope or in a flat or depressed area where soil deposition may be occurring (generally has dark organic soil at the surface),
c) Neither – a flat area with no evidence of deposition, transects with substantial rock or gravel, and bog bridging, roads, sidewalks, and streams.

9) **Tread Type (TT):** Record the *predominant* type of tread substrate material within a 20 cm (8 in) band centered on the transect, (under vegetation, leaves, or water) using these categories: 1=Soil/organic muck, 2=Bedrock, 3=Rock (from cobble to boulder), 4=Bog bridge (planks), 5=Boardwalk (decking/bridge), 6=Dirt or gravel Rd, 7=Paved Rd, 8=Rock step/rock-work, 9=Sidewalk, 10=Streams.

10) **Rugosity (R):** For a 3m (9.8 ft) segment of trail centered on the transect and looking uphill to identify the level of tread rugosity: 1=Smooth, few roots or rocks that would cause a hiker to slow or move laterally, 2=Intermediate, 3=Rough, lots of roots or rocks that would substantially slow hikers and cause them to move laterally and pick a way through.

11) **Offsite Vegetation (OV):** Record the predominant vegetation cover within a 2m (6.5 ft) band on either side of the trail,: 1=Organic litter and/or moss/lichen (shady) (rhododendron), 2=10-50% herbaceous vegetation cover, 3=51-100 herbaceous vegetation cover, 4=mostly grass and/or sedge cover (sunny), 5=mostly rock, little veg.

12) **Secondary Treads (ST):** Count the number of trails differentiated from the main tread by strips (>50cm) of mostly undisturbed vegetation or organic litter, regardless of their length, that closely parallel the main tread at the transect. *Do not count the main tread.*

13) **Organic Litter (OL):** Record the presence/absence and predominant type of organic litter off-trail in the vicinity of the transect: 1=Leaves, 2=Needles, 3=None to rare.

**Impact Indicators**

**Transect Establishment:** A great deal of judgment based on a variety of factors will determine the placement of the transect trail tread boundary stakes and measurement tape. Accurate and precise Cross Sectional Area (CSA) soil loss measures depend on your configuration of these items.
**Trail Tread Boundaries:** Examine the Figure 1 photos illustrating different types of tread boundary determinations. Tread boundaries are defined as the most pronounced outer boundary of visually obvious human disturbance created by trail use (not trail maintenance like vegetation clearing). These boundaries are defined as pronounced trampling-related changes in ground vegetation height (trampled vs. untrampled), cover, composition (broadleaf herbs vs. grasses), or when vegetation cover is reduced or absent, changes in organic litter (intact vs. pulverized) (see photo illustrations in Figure 1). The objective is to define the trail tread that receives the majority (>95%) of traffic, selecting the most visually obvious outer boundary that can be most consistently identified by you and future trail surveyors. Where helpful it is appropriate to examine the adjacent 3 meters on either side of the transect location to project trail boundaries from there to define the tread boundaries at the transect point.

- Include any secondary parallel treads within the transect only when they are not differentiated from the main tread by strips (>50cm) of mostly undisturbed vegetation or organic litter.
- If the trail is on stonework (rock steps, armored treads, stepping stones) use the width of stonework unless there is visible evidence of walking on bordering rocks or around them. Omit CSA measures (record a -1).
- If the trail is on a sidewalk, bog bridging, or boardwalk measure the width of the feature and omit the CSA measures (record -1). If there is a discernable trail on adjacent soil/veg/rocks then conduct transect and CSA measures there.
- Omit transect and CSA measures (record -1) if point is located on a road or creek.
- If the trail is on rock you may be able to reasonably deduce the tread boundaries based on vegetation (plants, moss, lichen) or rock trampling disturbance at the transect or as projected from adjacent areas. Conduct CSA measures only if you determine that the rock was originally covered by soil (otherwise record a -1). If one or both boundaries are still a complete guess, then record a -1 for tread width and CSA.

CSA soil loss measures also require different procedures based on the type of trail and erosion. Refer to Figure 2 and these definitions:

**Direct-ascent vs. side-hill trails:** Trails, regardless of their grade, that more or less directly ascend the slope of the landform are direct-ascent or “fall-line” trails. Direct-ascent trails involve little or no tread construction work at their creation – generally consisting of removal of vegetation and organic litter and then “walked-in.” Trails that angle up a slope and require a noticeable amount of cut-and-fill digging in mineral soil (generally on landform slopes of greater than about 10%) are termed side-hill trails. Soil excavation and fill work is required to create a gently out-sloped bench to serve as a tread. Separate procedures are needed for side-hill trails to avoid including construction-related soil movement in our measures of soil loss following construction.

**Recent vs. historic erosion:** Recreation-related soil loss that is relatively recent is of greater importance to protected land managers and monitoring objectives. Severe erosion from historic, possibly pre-recreational use activities, is both less important and more difficult to reliably measure. Historic erosion is defined as adjacent erosion that occurred in the past and is not currently within the tread. When trails follow old road-beds, bull-dozer work may also
have removed soil that will be indistinguishable from historic erosion. Including this form of soil loss as “historic erosion” is unavoidable.

a) **Direct-ascent trails, recent erosion:** Refer to Figure 2a. Place stakes and the transect measurement tape to characterize what you judge to be the *pre-trail original land surface*. Place the left-hand stake so that the bottom of the transect tape sits on what you believe was the “original” ground surface but at the edge of any tread incision, if present (see Figure 2a). This option generally always applies to shallow or deeply rutted trails with near-vertical sides.

b) **Direct-ascent trails w/historic erosion:** Refer to Figure 2b. If you judge that some of the erosion is historic then follow these procedures. There should be an eroded tread within a larger erosional feature. Place the stakes at the current trail tread boundaries and stretch the transect tape to allow measurements of the more recent recreation-related erosion (if present). For this configuration the tape should generally be slid all the way down the stakes to the ground so that the CSA measurements begin and end with 0 values. Perform the CSA measurements described below, then reconfigure the transect line to measure historic erosion by placing the stakes and tape to conform with the original land surface as depicted in Figure 2b. Then follow the Historic Erosion measurement guidance in the next section.

c) **Side-hill trail:** Refer to Figure 2c. The objective of this option is to place the transect stakes and tape to simulate the post-construction pre-use tread surface. When constructing side-hill trails upslope soil is excavated and shifted downslope as fill to create a gently out-sloped bench (most agency guidance specify a 3-5% outslope) for the tread surface (see Figure 2c). Outsloped treads drain water across their surface, preventing the buildup of larger quantities of water that become erosive. However, constructed treads generally become incised over time due to soil erosion, displacement, and compaction. *Note that a raised berm is often found along the lower edge of older side-hill trails. This may be from soil loss occurring from the tread but recognize that soil and organic litter displaced from the trail or the side-slope above the trail is often deposited here, raising the height of the berm above the “original” tread surface.*

Carefully study the tread in the vicinity of the sample point to judge what you believe to be the post-construction tread surface. Pay close attention to the tree roots, rocks, lichen/moss cover on rocks, and bath-tub rings or lines on the rock to help you judge the post-construction tread surface. Look in adjacent undisturbed areas to see the extent to which roots and rocks are exposed naturally or the approximate depth of their burial. Configure the stakes and transect line to approximate what you judge to be the post-construction pre-use tread surface. If a berm is present along the lower side of the trail use your judgment based on exposed tread roots and rocks to determine if the berm surface reflects the height of the post-construction tread surface or, as shown in Figure 2c, if it was raised by displaced tread or upslope soil. Determine the transect tape height on the metal stake on the side you are most certain of and affix it with a binder clip. If you are fairly certain of the tape height on the opposite side then pull the tape tight and affix it to the other metal stake. The slope of the transect line should generally be to the downhill side and be less than 5% or 3°. If uncertain,
assume that the original trail outslope was about 5% or 3° and affix the line on the opposite side based on a 5% or 3° outslope using the clinometer (this does not apply to fall-aligned trails). Note that in some circumstances configuring the transect tape will result in it being elevated above the base of either boundary stake so that the first or last vertical CSA measure is >0; this is acceptable.

d) **Side-hill trail with historic erosion**: Refer to Figure 2d. If you judge that some of the erosion is historic then follow these procedures. There should be an eroded tread within a larger erosional feature. Place the stakes at the current trail tread boundaries and stretch the transect tape to allow measurements of the more recent recreation-related erosion (if present). Perform the CSA measurements described below, then reconfigure the transect line to measure historic erosion by placing the stakes and tape to conform with the original post-construction tread surface as depicted in Figure 2d. Then follow the Historic Erosion measurement guidance in the next section. Note that in some circumstances configuring the transect tape will result in it being elevated above the base of either boundary stake; this is acceptable.

**Measurement Procedure**: Hammer the steel border stakes in at each tread boundary making sure that the transect line will be perpendicular to the tread at that location. If stakes can’t be inserted into the ground then have your partner hold it in place during the measurements, or move large rocks to sandwich the stake between them. The stakes have black marking located at 5 cm intervals, when possible insert the stakes so that the post-construction tread surface aligns with one of these markings. Place binder clips on the stakes so that the bottom of the binder clip aligns with what you judge to be the post-construction pre-use tread surface.

Stretch the transect measurement tape between the stakes configured using your best judgment to reflect the post-construction pre-use tread surface at the bottom of the tape. Refer to the above guidance under letters a-d for configuring the height of the transect measurement tape, noting the differences between fall-line and side-hill trails and those with historic erosion. If rocks or roots obstruct the transect tape then offset the tape upwards in 5 cm increments as needed following the guidance below. The tape on the left side should be affixed with a binder clip so the stake is at the “0” point of the tape, secure the opposite end by pulling the tape tightly, then wrapping it around the stake and securing with another binder clip. The tape needs to be tight - any bowing in the middle will bias measurements.

Take vertical soil loss measures **perpendicular to the measurement tape** every 10 cm along the transect tape beginning at the left-hand stake, measuring from the bottom of the transect measurement tape to the trail tread surface (measure through water to soil/rock and to the base of all organic materials; do not move rocks). Take and record these vertical CSA values to the nearest 0.5 cm (e.g., 3.0, 3.5, 4.0, 4.5 and so on). Note: if the trail is extremely wide such that CSA measures every 10 cm are too time-consuming (e.g., trail is >2m (6.5 ft) wide), then you can change the measurement interval to 20 cm; **be sure to record this change on the tablet data form!**

35
Measurement Tape Obstructions: For all transects, if the transect tape cannot be configured properly due to obstructing rocks or roots, then you must offset the line upward in 5 cm increments the same amount on both steel transect boundary stakes. Refer to the photo below, noting that both stakes should be adjusted up or down when possible so that one of the 5 cm markings is aligned with what you believe to be the post-construction tread surface. Leave a pair of binder clips on the stakes to show the location of the post-construction tread surface aligned with the bottom of the binder clips. Attach the offset tape with an additional pair of binder clips. If you use an offset be sure to call out and record on the tablet the exact amount of the offset in centimeters so that the offset distance can be subtracted from the CSA measures during data analyses.

14) Tread Width (TW): See prior “Trail Tread Boundary” guidance. Measure and record the length of the transect (tread width between the tread boundary stakes) to the nearest 0.5 centimeter (e.g., 45.0, 45.5, 46.0 cm). Omit for all roads and when tread boundaries are indistinguishable.

15) Cross-Sectional Area (CSA): See prior “Trail Tread Boundary” guidance. The objective of the CSA measure is to measure trail soil loss from the estimated post-construction pre-use tread surface to the current tread between the trail boundary stakes. Note that CSA soil loss measures reflect all of the following: erosion by water or wind, soil displacement from trail users, and soil compaction. Record all the vertical CSA measures based on the guidance above beginning at the left-hand stake. The tablet form software will calculate and provide the correct number of data entry spaces based on dividing the tread width by the tread interval.

16) CSA Transect Measurement Interval (TMI): This is normally 10 cm but can be changed to 20 cm for trails wider than 2 m or 200 cm. Record the interval value used for this transect.
17) **Transect Line Offset (TLO):** Record the transect line offset as 0 or the number of centimeters necessary to raise the transect tape above obstructing rocks or roots. Ensure that the line was offset equal amounts on both boundary stakes.

18) **Maximum Incision (MI):** Select and measure along the transect line the maximum incision value, recorded to the nearest 0.5 centimeter (e.g., 4.0, 4.5, 5.0 cm). Assess only when CSA is not -1.

**Transect Photos:** Take two photos of the transect with the stakes and transect tape configured as you measured it. **Oblique photo** – move the tablet back or forward along the trail until you capture the entire transect plus about 2 ft of adjacent terrain on either side of the transect stakes. Position the tablet so that the background looking down the trail beyond the transect is also captured. **Vertical photo** – hold the tablet directly above the transect tape and take a photo that includes both stakes (when possible) and shows the tread conditions. **Check both photos for focus and exposure and retake them when needed.**

**Metadata and transect link:** The photos are linked by the tablet form software to the transect field forms but we need a back-up if they somehow become un-linked. It is critical that the photos retain the “Date/time created” and the GPS metadata so that they can be linked to the date/time field for the transect form and the Trimble GPS averaged point saved for each transect.

19-28) **Tread Condition Characteristics:** Along a 20 cm (8 in) band centered on the transect, estimate to the nearest 10% (5% where necessary) the aggregate proportion occupied by any of the
mutually exclusive *tread surface* categories listed below. **Be sure that your estimates sum to 100%.**

<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S-Soil:</strong></td>
<td>All soil types including sand and organic soils, excluding organic litter unless highly pulverized and occurs in a thin layer or smaller patches over bare soil.</td>
</tr>
<tr>
<td><strong>L-Litter:</strong></td>
<td>Surface organic matter including intact or partially pulverized leaves, needles, or twigs that mostly or entirely cover the tread substrate.</td>
</tr>
<tr>
<td><strong>V-Vegetation:</strong></td>
<td>Live vegetative cover including herbs, grasses, mosses rooted within the tread boundaries. Ignore vegetation hanging in from the sides. Naturally-occurring rock (bedrock, boulders, rocks, cobble, or natural gravel). If rock or native gravel is embedded in the tread soil estimate the percentage of each and record separately.</td>
</tr>
<tr>
<td><strong>R-Rock:</strong></td>
<td>Naturally-occurring rock (bedrock, boulders, rocks, cobble, or natural gravel). If rock or native gravel is embedded in the tread soil estimate the percentage of each and record separately.</td>
</tr>
<tr>
<td><strong>M-Mud:</strong></td>
<td>Seasonal or permanently wet and muddy soils that show imbedded foot or hoof prints from previous or current use (omit temporary mud created by a very recent rain). The objective is to include only transect segments that are frequently muddy enough to divert trail users around problem.</td>
</tr>
<tr>
<td><strong>G-Gravel:</strong></td>
<td>Human-placed (imported) gravel on trail or road.</td>
</tr>
<tr>
<td><strong>RT-Roots:</strong></td>
<td>Exposed tree or shrub roots.</td>
</tr>
<tr>
<td><strong>W-Water:</strong></td>
<td>Portions of mud-holes with water, or water from seeps or creeks.</td>
</tr>
<tr>
<td><strong>WO-Wood:</strong></td>
<td>Human-placed wood (water bars, bog bridging, decking).</td>
</tr>
<tr>
<td><strong>O-Other:</strong></td>
<td>Specify: e.g. paved road or sidewalk.</td>
</tr>
</tbody>
</table>

**Historic Erosion:** Replicate the Transect Establishment Procedures from above to configure the tape measure to reflect any historic erosion if present. This alignment should disregard the current tread boundaries and instead reflect your judgement of any historic soil loss.

29) **Historic Tread Width (HTW):** Measure and record the length of the transect (tread width) to the nearest centimeter (e.g., 45.0, 45.5, 46.0 cm). Omit if CSA is a -1.

30) **Historic Maximum Incision (HMI):** Select and measure along the transect line the maximum incision value, recorded to the nearest 0.5 centimeter (e.g., 4.0, 4.5, 5.0 cm). Omit if CSA is a -1.

31) **Upper Trail Watershed Boundary (UTWB):** Walk in an uphill direction from the trail transect up to 50 m (164 ft) (determined by counting your paces) until you reach a point where you estimate that nearly all water running down the trail during a rainstorm would flow off the trail. This may due to a human-constructed water bar or drainage dip, a natural feature (e.g.,
39

Special Study on Mud-holes

We need a substantially larger sample of transects located at mud-holes to enable multiple regression modeling of the factors that contribute to the development of mud-holes and how we can design trails to prevent their occurrence. While hiking to, or when surveying each A.T. section, stop at every occurrence of mud-holes that are at least one meter long, including locations that are currently dry. The objective is to measure only mud-holes that are lasting, not ones that dry up two days after a rain. Establish a transect at the center of the mud-hole and assess it using the standard transect protocols. Label the transect with the letters “mud” followed by the nearest section and transect number and record an averaged point with the Trimble. In addition to the standard transect photos take additional photos clearly showing the lowermost “drainage” area and the principal area that is supplying water to the mud-hole.

35) **Source of water:** Determine the source of the water feeding the mud-hole:
   1) Spring or seep, 2) intermittent or perennial stream, 3) rain-water, 4) high water table (swampy area).

36) **Mud-hole Cause:** Determine why the mud-hole formed:
   1) Flat-terrain, tread has a rut or depression that retains water,
   2) Side-hill (sloping) terrain, tread has a berm and other obstructions that prevent water drainage.

37) **Ease of Correction:** Record the most appropriate response using your judgement:
1) Mud-hole could be easily drained by cleaning an existing drainage ditch,
2) Mud-hole could be drained by digging a new drainage ditch (<5 ft long x <1 ft depth),
3) Mud-hole could be drained by digging a new drainage ditch (5-10 ft long and/or 1-2 ft depth),
4) Drainage is too difficult, should consider trail relocation, boardwalks, stone steps, or other action.
Figure 1. Photographs illustrating different types of boundary determinations. Trail tread boundaries are defined as the most pronounced outer boundary of visually obvious human disturbance created by trail use (not trail maintenance like vegetation clearing). These boundaries are defined as pronounced changes in ground vegetation height (trampled vs. untrampled), cover, composition, or, when vegetation cover is reduced or absent, as pronounced changes in organic litter (intact vs. pulverized). The objective is to define the trail tread that receives the majority (>80%) of traffic, selecting the most visually obvious boundary that can be most consistently identified by you and future trail surveyors.
Figure 2. Cross sectional area (CSA) diagrams illustrating alternative measurement procedures for direct ascent trail alignments (a & b) vs. side-hill trail alignments (c & d) and for relatively recent erosion (a & c) vs. historic erosion (b & d)