Integrating Geospatial Technology and Ecological Research in Recreation Planning and Analysis of Sustainable Recreation Infrastructure

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ABSTRACT

This dissertation is an inquiry into two disciplines: recreation ecology and geospatial analysis. The dissertation consists of three journal article manuscripts focusing on the sustainability of recreational infrastructure components in backcountry and wilderness settings. Two articles focus on campsite conditions, nodal areas of visitor use and impact. The third article focuses on trail conditions, linear corridors of visitor use and impact. Campsites and trails comprise the most visited and impacted components of recreation infrastructure; locations where protected natural area visitors spend the majority of their time and where the majority of resource impacts occur. Resource conditions at these locations affect the quality of recreational experiences and are the focus of management and scientific efforts to measure and manage visitation-related resource impacts. The articles provide a strong scientific background to understanding ecological processes and better preparing recreation planners and managers for sustainable infrastructure management decision-making.

The first article assesses the sustainability of campsites over thirty-two years of use in the Boundary Waters Canoe Area Wilderness (BWCAW) in northern Minnesota. Differences in vegetation composition, tree cover and groundcover from 1982 to 2014 were measured. Paired t-tests analyzed significant ecological differences on campsites and paired controls over time. Best management practices for managing campsites for the long-term are suggested.

The second article analyzes the extent of non-native plants on campsites over thirty-two years. Paired t-tests were used to look at cover and abundance on campsites and control areas between 1982 and 2014. This paper explores ecological benefits and degradation incurred by non-native plants on campsites over time and discusses implications for wilderness character at BWCAW.

The third article is interdisciplinary, incorporating ground-based recreation ecology measurements with technical spatial analyses and modeling to improve understanding of erosional processes on trails. Fine resolution terrain data was used to examine terrain metrics as they relate to amount of soil loss. Multiple Linear Regression was used to test a number of variables taken from the field and derived from Geographic Information Systems (GIS) software using a 1m Digital Elevation Model. This paper explores relationships between different terrain variables and soil loss observed on the Appalachian Trail. It provides insights on which terrain features influence erosion and provides recommendations to trail managers to design more sustainable trails.

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CHAPTER 1: INTRODUCTION

The study of recreation ecology examines, assesses and monitors the biophysical impacts from visitors. Recreation ecology began in the late 1920s and 1930s with early observations of visitor impacts (Meinecke 1928; Bates 1935). Substantial scientific exploration of the field did not occur until the 1960s (Cole 1987a). It was in this era that backcountry visitor use sharply increased, as did the resource impacts. Active research and integration with management frameworks occurred in the 1980s with a refinement of recreation ecology methods and new topics occurring in the 1990s. In the 21st century, major research questions haves looked at: (1) types of recreation impacts that exist, (2) magnitude and significance of recreation impacts, (3) relationship between amount of use and intensity of impact, (4) use-related and environmental factors that contribute to the problem, (5) condition change over time, (6) effectiveness of visitor and site management actions, and (7) improvement of impact assessment methods (Leung and Marion 2000). Now, erosion control design techniques, restoration techniques, an international focus and new methodologies utilizing geospatial technologies are common themes (Zabinski et al. 2002; Cole et al. 2008; Cole 2013; Pickering et al. 2010; Wimpey and Marion 2011).

Understanding the degree of recreation impacts is essential for the management of wilderness and backcountry areas. Monitoring the amount of use and extent of ecological damage from visitors and analyzing the effectiveness of restoration strategies is crucial to fulfilling the dual mandate of many land management agencies to provide resource protection and recreation provision. Visitor impacts can be minimized when managers comprehensively understand the use related (type, amount, behavior), environmental (vegetation type, topography), and managerial (site design and management, visitor education and regulation) factors influencing impact. Since recreation is an allowable use of wilderness areas, it is up to managers to employ the best management practices in order to minimize impacts. The research presented in this dissertation focuses on long-term ecological impacts of camping and hiking on recreation infrastructure and employs cutting-edge science to help managers determine the best sustainability practices. This research advances the field of recreation ecology in adopting the latest geospatial technology and analytical techniques through the use of GPS devices for data collection, LiDAR-derived terrain models and GIS software for analysis of spatial phenomena.

The first article (Chapter 2) looks at long-term impacts to nodal recreation sites in the Boundary Waters Canoe Area Wilderness (BWCAW). Few longitudinal campsite studies using research protocols have been completed; monitoring datasets and research studies using monitoring ratings are more common. Of these, Merriam and Peterson (1983) looked at the difference in 15 years of use of 8 BWCAW campsites. They found that impact was related to campsite forest type, with aspen-birch sites being impacted the most and red pine or spruce sites impacted the least. A more complete study with a larger sample size is needed to determine the biophysical impacts of long-established campsites over decades of time.

Most long-term campsite study impacts look at the recovery rates of soil and vegetation from closing a campsite. Stohlgren and Parsons (1986) looked at campsite recovery in Sequoia National Park, finding that recovery rates differed spatially within each campsite. The central intensively trampled areas of campsites had lower plant species cover and higher soil compaction than peripheral areas.

Marion and Cole (1996) monitored resource conditions on river campsites over five years at Delaware Water Gap National Recreation Area in northeastern Pennsylvania. The intensity of campsite impacts was related to the amount of use and topographic position. Changes in soil and vegetation were less pronounced on campsites that had been open to use for a long time compared to campsites that were recently opened. Campsite impacts were found to increase rapidly at initial establishment, then stabilize with ongoing use. Campsites effectively closed to use experienced steady rates of recovery over five years due to productive soils, high soil moisture, and a long growing season.

The BWCA has served as an important study area for some of the very earliest recreation ecology research in wilderness. A baseline inventory of existing campsites within the BWCA was carried out by McCool, Merriam and Cushwa in 1969. This study determined that campsites on islands and along main canoe routes had greater impacts, which they attributed primarily to higher use levels. A study examining the effect of differing use levels on impacts found that even light use (0 to 30 days use/season) results in significant loss of ground cover (Frissell and Duncan 1965). Once an area is used as a campsite, trampling quickly results in loss of vegetative ground cover. Frissell (1978) developed a campsite condition class assessment that provides management guidance on when to close campsites based on the severity of soil erosion and plant vigor. Merriam et al. (1983) reported that campsites are most highly affected by initial site use.

Subsequent traffic results in diminishing amounts of ground cover impact. Some impacts do increase over time and with increasing use levels, notably exposed soil and soil compaction (Marion 1984). The first article (Chapter 2) presented in this dissertation assesses long-term ecological impacts and provides best management practices for managing campsites sustainably.

The second article in this dissertation (Chapter 3) focuses on the how camping has influenced non-native plant cover and abundance over time, and in turn impacts wilderness character. Agencies are mandated to monitor and protect wilderness character as described in the Wilderness Act of 1964. Wilderness qualities such as naturalness, untramelling and opportunity for un-confined primitive recreation and solitude are all considered under wilderness character monitoring (Landres et al. 2015).

The study of the movement of non-native species and the extent of their spread, and likelihood of further spread is of high importance in national protected areas. Introduction of non-native species by humans and the spread of these species that causes a shift in the species richness and ecosystem characteristics of an area and can be considered to be an impairment of the landscape. Recreationists such as hikers and campers are a source of introduction and spread of invasive species. Non-native plants can easily hitch a ride on clothing or equipment and can be carried for many miles (Pickering and Mount 2010; Barros and Pickering 2014; Wichmann et al. 2009; Whinam et al. 2005).

Sustained recreational use, camping for example, has impacts on the vegetation. Vegetation composition changes and floristic dissimilarity develops between campsites and off-site areas (Marion 1984). Plant species that do not do well with disturbance drop out, while plant species that are able to outcompete under disturbed conditions begin to take over. Invasive species that come in along trails can spread to adjacent areas through self-propagation (Pickering and Hill 2007). Non-native species then begin to spread to areas outside of the trail or campsite, impacting the surrounding ecosystem.

In the Boundary Waters Canoe Area Wilderness, researchers have found that non-native plants such as plaintain (*Plantago major*), red clover (*Trifolium pratense*), white clover (*Trifolium repens*), common dandelion (*Taraxacum officinale*), orange hawkweed (*Hieracium aurantiacum*) and Canada thistle (*Cirsium arvense*), have spread into the BWCAW along portage trail corridors (Dickens et al. 2005). Non-native species were consistently found within 1m of the trail, where human disturbance and trampling is prevalent. Non-native species were rarely found at distances of 50m from the trail. Chapter 3 documents the change in the spread, cover and abundance of non-native plants species on campsites and paired controls in the BWCAW. The paper explores the ecological benefits and degradation incurred by non-native plants on campsites over time and discusses implications for wilderness character at BWCAW. While canoeing and camping is a historical use of the area and a major part of why the BWCAW was established as wilderness in the first place, wilderness managers need to consider the long-term impacts that camping has to the ecosystem in their strategy to continue to protect wilderness character.

The third paper in this dissertation, Chapter 4, employs geospatial techniques to model soil erosion along a section of the Appalachian Trail in New Hampshire. The Appalachian Trail offers opportunities for backcountry recreation and long-distance hiking and receives an estimated two million hikers a year. Recreation activity ultimately causes impacts to the ecosystem, and impacts to soil are irreversible. Trail managers spend a lot of time and resources maintaining the current trail system to withstand the level of traffic that it receives. Many parts of the Appalachian Trail were adopted into the official trail system after originally being built as roads or by users. As such, the trails are not often in the best alignment in terms of erosion processes. Efforts to monitor trail conditions and fix sections that are badly eroding is time intensive as the trail covers over 2,000 miles. Previous work has been done to pinpoint characteristics of trails that provide the most sustainable alignment, a trail that is hydrologically invisible and will resist erosion over time (Bratton et al. 1979; Leung and Marion 1996; Marion and Olive 2000; Wimpey and Marion, in press). To cover a broad trail system in a minimal amount of time, this study introduces using LiDAR to model trail erosion potential by utilizing detailed topographic metrics available from remote sensing technology.   Terrain metrics such as slope, aspect, topographic roughness, curvature, and hydrology attributes such as watershed size, flowlength and flow accumulation were derived in GIS using 1m LiDAR-developed Digital Elevation Model. This study compares GIS-derived metrics with field collected metrics, and adds novel variables that could only be developed with GIS software.

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CHAPTER 2: SUSTAINABLE CAMPSITE MANAGEMENT: LONG-TERM ECOLOGICAL CHANGES ON CAMPSITES IN THE BOUNDARY WATERS CANOE AREA WILDERNESS, MN

Abstract

The U.S. Forest Service manages nearly 2000 campsites in the Boundary Waters Canoe Area Wilderness. In the summer of 2014, we re-measured 81 campsites and their paired control plots from a study done in 1982 evaluating how vegetation and soil conditions have changed following 32 years of use. Long-term investigations of visitor impacts to protected natural areas are rare, yet knowledge of long-term changes is important to managers charged with making recreational visitation sustainable.

Our findings reveal substantial changes in area of exposed soil, soil erosion, and vegetation cover on the campsites. Average soil loss on campsites was estimated at $17.2m^3$. Although mean campsite size is unchanged, the proportion of campsite area in the “core” has decreased, shifting some use and impact into peripheral “satellite” tenting areas just beyond campsite borders. The ecology of campsites has been altered primarily by a significant reduction in number of campsite trees and tree cover. The number of trees per hectare decreased by 44% on campsites from 1982 to 2014. Visitors are harvesting trees for firewood, and young seedlings are not able to withstand high trampling pressure. Campsites are expected to continue losing trees without replacement into the future.

Sustainable campsite Best Management Practices to reduce these impacts include selecting resistant sites, such as those with a bedrock boat landing or that are topographically constrained to resist expansion in size. Construction and maintenance of campsite tent pads can attract and spatially concentrate camping activities, helping to deter site expansion into offsite areas. The placement of large rocks and downed trees can help close unnecessary boat landing areas to prevent soil loss along the shoreline.

Keywords: recreation ecology, campsite management, sustainable recreation management, long-term campsite impacts, wilderness

Introduction

Wilderness, as defined in the Wilderness Act of 1964 (Public Law 88-577), is managed to protect its natural conditions, where the imprint of human work is substantially unnoticeable. Wilderness areas are administered so as to leave them unimpaired for future generations through the preservation of wilderness character. Opportunities for unconfined recreation is a pillar of the conditions for Wilderness to be designated. The goal of wilderness managers is to allow recreation without degradation to the area or trammeling of wilderness character. For this to occur in perpetuity managers need to know more about long-term ecological changes on campsites to inform the selection and management of campsites that can sustain high use with minimal degradation.

Environmental degradation from camping activities can contribute to a wide range of resource impacts that vary by type and severity. Even low levels of trampling disturbance in areas adjacent to campsites from activities such as firewood gathering can reduce ground vegetation height, cover, and biomass (Cole 1995a, 1995b, Marion et al. In Press, Sun and Liddle 1993). Higher levels of trampling on campsites lead to more complete ground vegetation loss, or compositional changes as fragile plants are replaced by more resistant species (Cole 1995b; Marion and Cole 1996). Concentrated traffic also pulverizes soil leaf litter and humus layers, which are either lost through erosional processes or intermixed with underlying mineral soils. These soils then become exposed and vulnerable to wind or water erosion and compaction (Marion et al. In Press, Monti and Mackintosh 1979). The compaction of soils decreases soil pore space and water infiltration, which in turn increases water runoff, muddiness, and soil erosion (Marion et al. In Press, Manning 1979).

The purpose of this study is to measure, characterize, and analyze resource conditions and long-term ecological changes on campsites in the Boundary Waters Canoe Area Wilderness (BWCAW) in northern Minnesota. Few longitudinal research studies evaluated with vegetation, soil, and physical measurement protocols have examined campsites and paired controls, although Cole and coauthors (Cole 1986, Cole 2013, Cole and Parsons 2013, Cole et al. 2008) have reported results from several monitoring studies employing rapid assessments and ratings. For example, in the Eagle Cap Wilderness, Cole et al. (1986) found that exposure of mineral soil increased on campsites, and the median number of felled-trees counter per year increased over time while vegetation cover remained stable. In Grand Canyon National Park, backcountry campsites were monitored over 20 years and campsites size was found to remain stable. While high-use sites receive more disturbance than low-use sites, disturbance to sites by use level stayed consistent over time. Within the BWCAW, Merriam and Peterson (1983) examined changes on eight campsites over 15 years of use. They found that impact was related to campsite forest type, with aspen-birch sites impacted the most and red pine or spruce sites impacted the least. However, none of these studies included detailed long-term ecological measurements of both campsite and paired "control" site conditions, such as tree, shrub, and ground vegetation cover and composition. A more comprehensive study with biophysical measurements and a larger sample size is needed to improve our understanding of long-term ecological changes and their implications for sustainable camping management.

The BWCAW has served as an important study area for some of the very earliest recreation ecology research in wilderness. A baseline inventory of existing campsites within the BWCAW was carried out by McCool, Merriam and Cushwa in 1969. This study determined that campsites on islands and along main canoe routes showed greater human impacts, which they attributed primarily to higher use levels. A study examining the effect of differing use levels on impacts found that even light use (0 to 30 days use/season) resulted in significant loss of ground cover (Frissell and Duncan 1965). Once an area is used as a campsite, trampling quickly results in loss of vegetative ground cover. Merriam et al. (1973) also reported that campsites are most highly affected by initial site use. Subsequent traffic results in diminishing amounts of ground cover impact. However, some impacts do increase over time and with increasing use levels, notably exposed soil and soil compaction.

Marion (1984) examined ecological changes on 96 BWCAW campsites and paired control sites in 1982, documenting significant changes to vegetation and soil (Marion and Merriam 1985a). Root exposure occurred on 84% of trees on the typical BWCAW site. Tree damage was found on nearly all of the sites, consisting of large branches cut or broken off, trunk scarring from axes, and bark stripping. Tree seedlings and saplings were virtually eliminated on campsites, presumably most were removed during initial campsite creation and use. Vegetative ground cover declined from an average of 94% offsite to 36% onsite. The durability of vegetation cover increased significantly with increasing sunlight at the ground surface, revealing that shade-tolerant plants are particularly susceptible to trampling while sun-loving plants (primarily grasses and sedges) are trampling-resistant. For example, mean dense vegetation ground cover was only 4% on campsites with 75-100% tree cover, but increased to 52% on campsites with less than 25% tree cover (Marion and Merriam 1985b). Plant composition on campsites was significantly different from control areas, many campsite plants were trampling-resistant non-native species (Marion et al. 1986). Soil compaction was significantly higher on campsites compared to controls. Compaction reduces soil pore space and water/air infiltration, increasing water runoff and erosion rates (Marion and Merriam 1985b).

Marion (1984) also found campsite use level an influential factor. The majority of change occurs between low and intermediate levels of visitation. However, the impact/use relationship varies considerably from one type of impact to another. For example, the amount of exposed soil relates linearly to the level of use - approximately 50% of the soil exposure occurring on sites receiving 60+ nights/year occurs on sites receiving 30 nights/year – but loss of vegetation and organic litter cover reveal a more curvilinear rate (approximately 70% of the vegetation loss occurring on campsites with 60+ nights/year of use has already occurred on campsites experiencing use just 10 nights/year). Tree seedling loss occurs even more rapidly, with nearly 95% loss on campsites receiving only 12 nights/year. Overall, sites utilized only 1-12 nights/year were approximately two-thirds as impacted as sites used 60+ nights/year. More heavily used sites had greater impact but the rate of increase in impact diminishes with increasing use.

Recovery rates on campsites differ substantially depending principally on plant community type, soil factors, and climate. Marion (1984) found evidence that recovery rates on closed campsites were considerably slower than initial impact rates for new campsites, based on comparisons to control plots. Marion estimated that these sites would regain near-natural conditions in approximately 20 years for vegetative ground cover, 60 to 70 years for vegetative composition, and 30 to 40 years for soil compaction. Sites that had been more heavily used and impacted had lower recovery rates and longer recovery times. A BWCAW campsite restoration, rehabilitation, and maintenance program seeks to enhance the sustainability of campsites kept open to use, as described in Marion and Sober (1987). Actions suggested to enhance campsite sustainability include a designated camping policy to direct camping on durable sites, visitor entry point quotas to pair visitor numbers to site numbers, group size restrictions to limit campsite expansion, and using native materials and plant species to reduce the area of impact on campsites and rehabilitate eroded areas. Cole (1992) noted that the spatial concentration of visitor activity on campsites enhances sustainability by increasing the proportion of time spent in the central part of the campsite, reducing trampling to peripheral areas. Wilderness research at Isle Royale National Park found that developing side-hill campsites, where sites are constructed within sloping terrain, was highly effective in limiting the areal extent of camping impact (Marion and Farrell 2002).

In this study, we evaluate sustainability of campsites in the BWCAW by quantifying an array of biophysical changes over 32 years. The U.S. Forest Service restricts the majority of BWCAW camping to designated campsites, so maintaining their natural conditions and limiting resource impacts over time are core management objectives. The management of campsites able to sustain high use while keeping associated resource impacts within acceptable limits is extremely challenging given the area's strong resource protection mandate and high visitation.

Study Area and Methods

The Boundary Waters Canoe Area Wilderness (BWCAW) is a 1,090,000-acre wilderness area in northeastern Minnesota, administered by the U.S. Forest Service, Superior National Forest. Designated as wilderness by the 1964 Wilderness Act, it has long been one of the most visited wilderness areas, with approximately 250,000 visitors annually. With over 1000 lakes, the area's primary recreational activities include canoeing and fishing. There is a permit season from May 1 to September 30 and party size is limited to 10 people. Most of the area is designated as non-motorized but there are sections where motorized use is allowed. The Forest Service currently provides 1,957 designated campsites in the area, most of which have a shoreline boat landing, primitive pit toilet, and steel fire grate.

The soils in the area are derived from glacial deposits, covering a thin mantle of glacial-till and lacustrine sediments (Prettyman 1987). The area receives between 66 and 78 cm of precipitation per year, with 40% falling as snow. The average summer and winter temperatures are 20^{o}C and -11^{o}C, respectively. The area includes habitat dominated by a jack pine forest *(Pinus banksiana Lambert)* associated with red pine (*Pinus resinosa)* and white oak *(Quercus alba L.)*; Great Lakes pine forest dominated by white pine (*Pinus strobus L*.) and red pine (*Pinus resinosa Aiton)* associated with paper birch (*Betula papyrifera Marshall*); and, northern boreal hardwood-conifer forest dominated by big-toothed aspen *(Populus tremuloides),* paper birch *(Betuala papyrifera),* balsam fir *(Abies balsamea L.),* white spruce *(Picea glauca Moench),* and white cedar *(Thuja occidentalis L.)* (Moyle and Moyle 1977).

This study replicates Marion's 1982 doctoral study of 96 wilderness campsites and controls (Marion 1984). We measured resource conditions such as root exposure, tree damage, ground cover, plant composition, soil compaction, and depth of organic soil horizon. At each campsite measured, a circular control plot of 50m^2 (size determined based on species area curve from nested plot technique) was measured for the same characteristics. Each control plot was environmentally similar to the campsite it is paired with; it had the same soil type, ecological land type, aspect, slope, soil depth to bedrock, and distance to water.

Sites were originally selected in the 1982 study to be within the USFS Kawishiwi District near Ely, MN. A stratified random sample was employed with sites equally distributed among three use levels and five ecological land types. An effort was made to relocate and measure the same sites in the 2014 study. Several sites were omitted if found to be severely affected by wildfire or windthrow, or had been closed. Eighty-one sites were re-measured in July and August of 2014 using the same 1982 protocols.

At each campsite, the size of the core site and satellite tenting sites were measured and combined to get a total campsite size. A satellite site is one that is separate from the main site around the fire grate, located in the adjacent offsite areas and accessed via a short trail. These were informally created by visitors for use as tenting spots, though tenting also occurs in the core site areas. The number and area of individual satellite sites and boat landings were recorded. Aggregate soil loss on the campsite was estimated in 2014 by measuring average depth of soil loss on the core site, access trail, and landing area separately and multiplied by the size of each area.

All plants were identified to the species level and assessed for cover with a modified quadrat method with whole-area determinations for both campsite and control plots. Coverage values were then aggregated by growth habit to obtain cover estimates for tree, shrub, herbaceous, and grass cover. Coverage estimates were also assessed for "ground cover," where the ground was classified as either bare soil, exposed bedrock, exposed roots, litter, sparse vegetation or dense vegetation. In the following data tables, sparse and dense vegetation cover values were combined to record "ground vegetation", indicating anything that was non-woody plant cover and under 1m tall. Areal measures of ground vegetation loss and exposed soil were calculated by using the percent cover estimates and multiplying them by campsite size.

For campsites, the number of living trees, seedlings, and stumps were counted and divided by campsite sizes to obtain standardized per hectare values. At each site and control, a 4-class ordinal scale rating was used to determine site expansion potential based on judging constricting topography and vegetation surrounding the campsite. Sites with high expansion potential are surrounded by flat terrain and sparse vegetation, while steeper terrain and dense vegetation contribute to a low expansion potential rating. To evaluate the efficacy of this expansion rating we analyzed differences in campsite size from 1982 to 2014 for this metric.

Visitor use level estimates were acquired from a U.S. Forest Service computerized travel model and knowledgeable wilderness managers in 1982 and 2014 (Marion and Merriam 1985). Campsites were divided into the same discontinuous level of use groupings used in the 1982 study: 1) low use (<12 nights/yr); 2) moderate use (20-40 nights/yr); and 3) high use (>60 nights/yr). Of the campsites measured in 2014, only campsites that fell into the discontinuous categories were used in analyzing impacts of level of use.

Other characteristics recorded included campsite age (retrieved from USFS records) and site maintenance, such as tent pad improvement or ruination, rock work, or site closure (from visual assessments and USFS records). Photos taken in 1982 of the core area around fire grates and of landing areas were replicated in 2014.

The 1982 and 2014 data were compared in a series of paired t-tests using SAS JMP software. Data were transformed and outliers removed in order to achieve a normal distribution and the use of parametric tests. Campsite and control measurements from both years were analyzed separately to evaluate change on each. Campsite values were also compared to their control values using a paired t-test to examine how recreation activity impacts vegetation and soil attributes. ANOVAs were conducted to investigate the influence of level of use and site expansion rating.

Results

Change in campsite area of disturbance

From 1982 to 2014 the campsites remained approximately the same size (p-value = .150). However, the sizes of different portions of the campsites did change over time. The campsite core area diminished an average of 31 m^2, while the combined area of satellite tenting sites increased significantly by 18 m^2 (Table 2.1). For all 75 campsites there was a small 6.8% reduction in the aggregate area of camping disturbance over the 32 years.

Table 2.1. Changes in the mean sizes of campsite core and satellite areas from 1982 to 2014.

Campsite Area	Mean 1982 (m^2)	Mean 2014 (m^2)	Mean Diff. 1982-2014 (m^2)	P-value[a]	Aggregate Measures (m^2)		
					1982	2014	Diff.
Core (n=74)	191	175	-16 (75)[b]	.006	17351	12798	-2274
Satellite (n=75)	10	28	18 (27)	<.001	802	2149	1335
Total (n=75)	201	203	2 (81)	.150	16569	15447	-1121

[a] Paired t-test, N distribution; [b] Standard Deviations.

The adjacent offsite satellite tenting areas are created by visitors. USFS staff seek to discourage their use by covering them with brush or downed wood and by providing 3-5 good tent pads within the core campsite area (though low staffing limits the number of sites that can be worked on). The mean number of tent pads per site in 1982 was 4.0, with an average of .56 satellite sites. In 2014, the mean number of tent pads was 4.4 with 1.4 satellite sites per campsite. While the number of tent pads increased by 10% but not significantly at the 0.05 level, the number of satellite sites more than doubled (p=<.001).

In the original selection of designated campsites, USFS managers often adopted existing visitor-created sites. Over time the staff closed campsites on small islands and in areas that had insufficient soil to support pit toilets, replacing them when possible with less erodible sites that had bedrock shorelines. A recommendation from Marion (1984) was to select campsites that were topographically constrained by steep slopes, rockiness, wet soils, or thick woody vegetation along the perimeter or in adjacent offsite areas. The likelihood of the campsite area expanding over time is lower when these conditions are present. A rating was applied in 1982 to evaluate the site expansion potential of each campsite.

Table 2.2 shows the results of an ANOVA to test the predictive success of the site expansion rating against change in campsite size over time. A high rating means that the campsite will likely expand due to an off-site area that is relatively level, free of large rocks, and with sparse vegetation and good drainage. A rating of “Very Poor” is a campsite that is more likely to resist expansion due to off-site areas that are unsuitable to tenting due to steep slopes, rockiness, dense vegetation, and/or poor drainage. While the ratings applied in 1982 do indicate predictive data for core and total campsite size there is variability in the findings that prevent statistically significant differences ($p>.05$).

Table 2.2. Effectiveness of campsite expansion ratings applied to campsites in 1982 evaluated by mean changes in campsite size over 32 years.

Campsite Size	Campsite Expansion Potential Rating				F-Ratio	P-value
	High (n=8)	Moderate (n=42)	Poor (n=24)	Very Poor (n=7)		
Core (m^2)	230 (432)[a]	194 (410)	171 (297)	108 (134)	1.7	.181
Satellite (m^2)	55 (101) (n=7)	38 (68) (n=31)	39 (69) (n=17)	40 (80) (n=4)	1.0	.149
Total (m^2)	288 (538)	222 (424)	207 (293)	136 (212)	1.9	.122

[a] Standard Deviation.

The impact of use on campsites includes not just a spatial component, campsite size, but also the severity of environmental degradation. Soil erosion is perhaps the most important long-term measure of degradation. Soil erosion was estimated only in 2014 (Table 2.3). The mean aggregate campsite soil loss is 17.2 m^3, with the majority occurring on the campsite core due to its large size. Mean incision values were greatest, 24 cm, at boat landings, where vegetation cover is removed by boats and feet and the wave action from wind and motorboats exacerbated shoreline soil loss. Satellite tenting areas did not exhibit erosion as most of these areas are fairly flat and receive relatively little foot traffic. When the mean soil loss per campsite is extrapolated to the 2000 BWCAW campsites, an aggregate estimated 33,660 m^3 of soil has been lost due to camping activities.

Table 2.3. Estimated campsite soil loss, 2014 data.

Campsite Component	Mean Incision Depth (cm)	Mean Soil Loss (m^3)
Trails (n=35)	9	0.9
Boat Landings (n=70)	24	4.9
Campsite Core (n=80)	6	11.4
Total (n=80)	7	17.2

The loss of vegetation cover and exposure of soil are other important components of impact from recreational traffic and camping activities. Table 2.4 characterizes percent and areal measures for these indicators by subtracting 1982 values from 2014 values to show changes going forward in time. Exposed soil on the campsites increased 8.2% for an average of 16.8 more square meters of soil exposed. However, vegetation cover also increased on campsites, with 16.3% more vegetation cover in 2014. Vegetation cover on the controls decreased an average of 18.3% as controls got more shade from denser canopy cover. Regardless, vegetation cover on campsites remains 22.6% more reduced on campsites than on their paired control sites in 2014 (Table 4).

Figure 1 presents mean groundcover changes on campsites from 1982 to 2014. Dense and sparse vegetation cover both increased substantially, equivalent to an equal reduction in the percent cover of organic litter. This is consistent with photo evidence of long-term trends, illustrated in the Figure 2 photos. These campsites have been in use for more than 40 years and many campsite trees have been lost without replacement. Tree loss and increased sunlight appears to be favoring an increase in trampling-resistant grass and sedge cover in the less trafficked peripheral use areas. For example, campsites in 2014 have 41.7% graminoid cover compared to 3.2% on neighboring control areas. Herbaceous cover of forbs is 6.6% on campsites versus 29.2% on controls.

Table 2.4. Changes in exposed soil and ground vegetation cover on campsites and controls from 1982 to 2014.

Indicator	Change: from 1982 to 2014				Change: 2014	
	Camp – Camp		Control – Control		Camp - Control	
	Mean	P-value	Mean	P-value	Mean	P-value
Exposed Soil (%)	8.2 (14)[a]	<.001	.3 (1.4)	.0467	18.3 (15.1)	<.001
Exposed Soil (m^2)	16.8 (38)	<.001	1.6 (6.8)	.0467	N/A	N/A
Vegetation Cover (%)	16.3 (27)	<.001	-18.3 (24.2)	<.001	22.6 (33.7)	<.001
Vegetation Cover (m^2)	62.0 (103)	<.001	-9.2 (28.7)	<.001	N/A	N/A

[a] Standard Deviation.

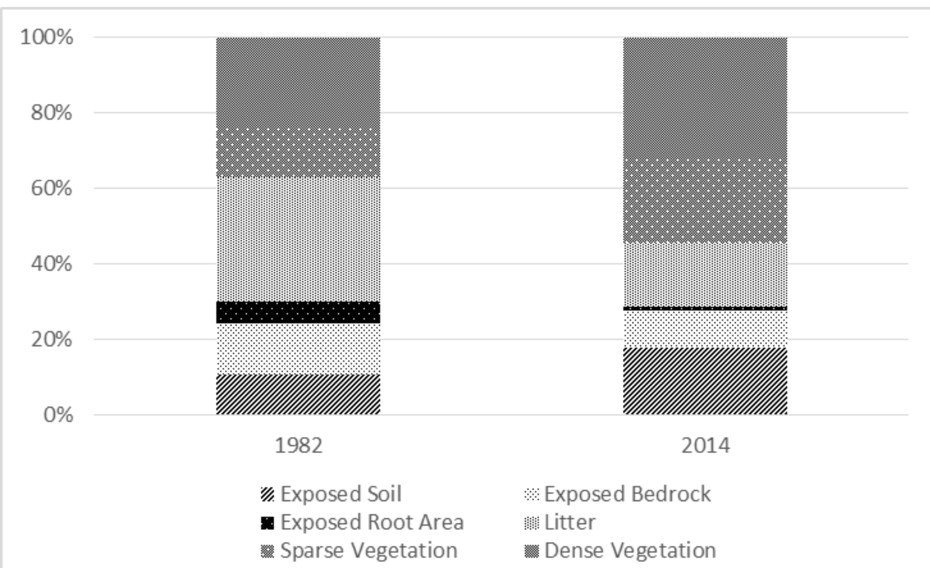

Figure 2.1. Groundcover changes on campsites from 1982 to 2014.

1982 **2014**

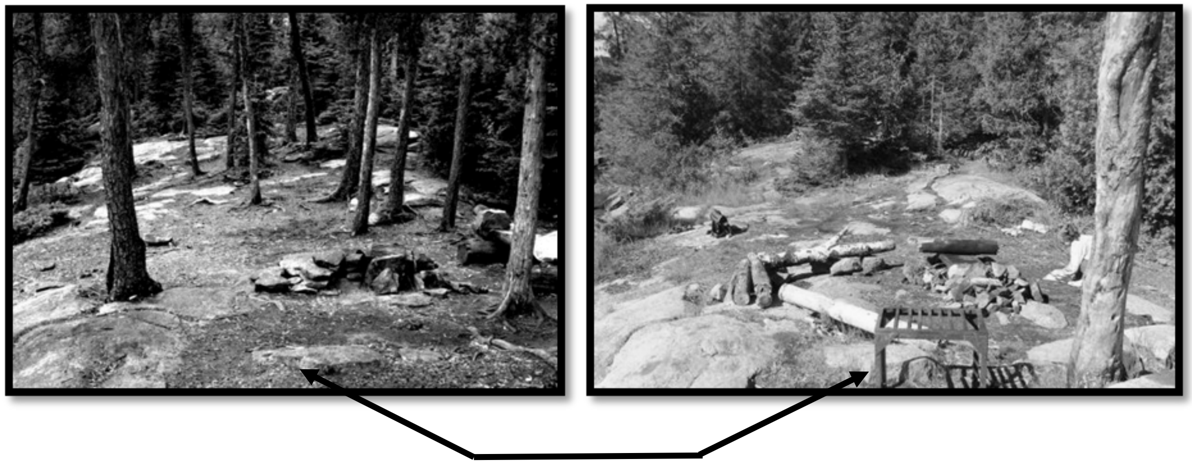

Figure 2.2. Photo comparison of tree loss and groundcover changes over time at a representative campsite.

Influence of camping on forest structure

Forest structure both on and off BWCAW campsites. has changed substantially in the three decades since the 1982 study. The forests are more mature in 2014 and have greater tree canopy cover and density, resulting in less herb and grass cover and greater moss cover in control areas (Table 2.5). In contrast, the campsites lost trees and tree cover and gained ground vegetation over 32 years. All components of the forest structure are significantly altered on campsites in 2014 based on paired comparisons to control values. The most substantial change is shrub cover, reduced 42.1% on campsites, followed by reductions in tree cover (28.7%) and moss cover (19.5%) (Table 2.5). Due to the high density of woody vegetation in control areas and greater sunlight on campsites, the amount of herbaceous and grass cover on campsites is 14.5% greater than on controls.

Table 2.5. Changes in tree, shrub, herb/grass, and moss cover on campsites and controls from 1982 to 2014.

Indicator	Change: from 1982 to 2014				Change: 2014	
	Camp – Camp		Control – Control		Camp - Control	
	Mean	P-value	Mean	P-value	Mean	P-value
Trees (%)	-10.5 (34.7)[a]	.001	6.3 (27.7)	.044	-28.7 (30.1)	<.001
Shrubs (%)	-3.9 (9.7)	<.001	0.8 (47.1)	.876	-42.1 (34.8)	<.001
Herb/Grass (%)	10.3 (39.4)	.004	-42.8 (36.1)	<.001	14.5 (35.7)	<.001
Moss (%)	0.2 (7.4)	.859	11.6 (11.8)	<.001	-19.5 (26.5)	<.001

[a] Standard Deviation.

The number and density of trees on campsites has significantly declined over the 32-year study period. On the 81campsites studied, an average of 64.6 trees per hectare have been lost from 1982 to 2014, due to a combination of factors such as felling by visitors for firewood and mortality from tree damage, root exposure, and natural causes (drought, insects, disease, fire, and lightning) (Table 2.6). Within campsite boundaries 384 tree stumps were counted in 2014; an additional 1054 stumps were counted in adjacent offsite areas, predominantly harvested by visitors for firewood. Such cutting has led to a significant decrease in the number of trees on and around campsites, reducing tree canopy cover and increasing the amount of sunlight reaching the ground (Figure 2). A significant number of tree seedlings have also been lost. In addition, due to visitor trampling and cutting, tree seedlings are rarely able to establish, grow, and reach maturity on campsites, suggesting that the historical deforestation of campsites will continue.

Table 2.6. Change in the number of trees, tree seedlings, and stumps per hectare on campsites from 1982 to 2014.

Indicator	Mean Diff. 1982 to 2014	P-value
Camp to Camp		
Trees/ha (n=78)	-64.6 (303.5)[a]	.031
Seedlings/ha (n=75)	-50.9 (152.8)	.002
Stumps/ha (n=79)	-1.7 (190.6)	.467

[a] Standard Deviation.

Influence of level of use on ecological changes to campsites

The relative differences in resource conditions for campsites at low, moderate, and high use are presented in Table 2.7. Note that the reported values were computed by subtracting 2014 campsite values from 1982 campsite values, with no comparison to their controls. The only exception was campsite soil loss, which was only measured in 2014. This measure and the percentage of trees with exposed roots were the only two indicators found to be statistically significant. Low use sites lost significantly less soil and had fewer trees with exposed roots than the high use sites. There is no statistical evidence that other characteristics, such as campsite size and the number of landings and satellite sites per campsites, increase as might be expected with increasing use.

Table 2.7. Relative changes in resource conditions on campsites from 1982 to 2014 as influenced by level of use.

Indicator	Low Use (N=6)	Medium Use (N=25)	High Use (N=27)	F-value	P-value
Vegetation Cover	Mean Values				
Tree (%)	-25.5 (32.7)[a]	-4.3 (38.1)	-15.4 (34.3)	1.1	.336
Shrub (%)	0.1 (1.9)	-4.5 (12.9)	-4.6 (10.2)	0.5	.627
Herb/Grass (%)	33.8 (49.1)	10.7 (42.1)	23.8 (26.8)	1.4	.252
Moss (%)	6.3 (17.4)	0.7 (3.0)	0.2 (5.9)	1.5	.224
Ground Cover					
Exposed Soil (m^2)	6.8 (19.4)	14.8 (41.2)	25.9 (43.3)	0.8	.457
Campsite Metrics					
Core Campsite Size (m^2)	-13.7 (192.7)	-72.3 (291.3)	-183.0 (401.1)	0.9	.397
Satellite Area (m^2)[b]	1.3	86.8 (81.5)	106.3 (111.2)	0.2	.785
Landings (#/site)	1.3 (0.8)	1.4 (0.6)	2.1 (0.9)	4.3	.246
Satellite (#/site)	-0.2 (0.4)	1 (1.4)	2 (1.5)	1.9	.154
Erosion					
Total Erosion (m^3)[c]	2.5 (2.9)	4.1 (3.6)	7.5 (3.3)	8.6	.001
Exposed Roots (%)	-0.5 (4.0)	-2.7 (3.8)	-6.5 (5.0)	7.1	.002

[a] Standard Deviation.
[b] N=1 for low use.
[c] Measured only in 2014

Discussion

Long-term trends in campsite condition

BWCAW managers have embraced a "containment" strategy for minimizing camping impact where camping is limited to designated sites. Previous research has found that in areas of moderate to high use a containment strategy is more effective than a dispersal strategy or unregulated camping (Reid and Marion 2004, Leung and Marion 1999, Marion In Press). The USFS has designated campsites with fixed fire rings and a travel zone-based reservation system to match the distribution of visitors and sites. The data from this study demonstrate mixed levels of success for a containment strategy implemented over several decades.

On the one hand, the amount of disturbed area over time (campsite numbers and sizes) have remained relatively unchanged over 32 years, suggesting that containing visitors in designated sites has been effective. On the other hand, the proportional changes from the core to satellite site sizes signify a shift over the 1982-2014 period in the way that visitors are using campsites and how they spatially distribute themselves on them. This may reflect that many campsites receiving a heavy use are located on main thoroughfares and serve as common campsites for larger groups, such as Boy Scouts. Larger group sizes may result in higher pressure to find enough tent pads, leading to an expansion into the forest and an enlargement of the campsite area of disturbance. Vegetation cover has also increased on campsites. However, campsites are clearly losing trees over time without replacement, which is contributing to increased vegetation compositional change. Though we lack data from 1982 for comparison, we also expect that soil loss occurs on campsites at a low but steady rate over time and that this is cumulative.

In general, the level of impact a recreational site receives generally relates to the amount and intensity of visitor use (Cole 1993, Monz et al. 2013); that is, high levels of use contribute to higher impacts, including reduced vegetation cover, greater soil loss, and larger campsite sizes. However, with stable use levels, impacts such as campsite size and vegetation cover tend to reach an equilibrium over time (Cole et al. 2008) while soil loss and loss of trees continue to occur and accumulate over time.

Area of Disturbance

While the change in mean campsite size over the 1982-2014 period is not statistically significant, the number of visitor-created satellite tenting areas has doubled from 1982 to 2014, and the core campsite area has contracted in size. Stable campsite sizes in the BWCAW area appear consistent with findings in Grand Canyon National Park, where researchers also found an increase in the number of campsites (Cole et al. 2008). While our BWCAW research did not focus on inventorying new campsites, new satellite tent pads have been created over time. Our data reveals a change in use patterns, a shift in tenting from core to satellite areas. We suggest three possible explanations. First, soil erosion over the decades of use has made tenting areas located in the core area less usable due to exposed rock and roots. This was observed during our assessments, while the newer off-site satellite tenting areas had smooth non-eroded substrates that were more comfortable for tenting. Second, discussions with USFS staff revealed a long-term trend of campers shifting to smaller and more numerous tents, which require more tenting spots. And third, campers may be placing a higher priority on shade from the sun, privacy, solitude, and natural quiet (distance from those who talk or snore). Our data suggest that campers are “voting with their feet” by creating these new and more desirable off-site tenting areas.

Forest Structure

Substantial changes have occurred to the forest structure and vegetation composition on campsites over time. Previous studies show that onsite tree mortality rates greatly exceed off-site rates and that successful tree regeneration on campsites is rare (Cole 1986; Marion and Merriam 1985a). Our findings mirror these. Comparison of campsite/control data on tree density, cover, and recruitment over 32 years characterize the extent of tree loss and canopy opening over campsites. The significant loss in trees and seedlings over the periods illustrates a dramatic change to the forest structure on campsites. The trend of tree loss without replacement on campsites will continue unless management action is taken. A substantial majority of the cut trees on and near campsites were in the 5-15 cm diameter class – the ideal size for firewood. Loss of trees due to malicious damage and firewood cutting are entirely “avoidable” recreation impacts (Marion 2014).

The loss of trees is a highly visual human impact within the wilderness. Campsites can increasingly be spotted from long distances across lakes due to their openings in the tree canopy. Campers may also dislike the increasing lack of shade on campsites. Our data reveal that there are 21 more sites in full sun today than in 1982 and we expect this trend to continue. Visitor use management frameworks direct managers to define “desired resource conditions” and for campsites this should address the acceptability of tree-less campsites in forested settings (Marion

In Press). Previous long-term studies were based on monitoring data, which generally do not assess amount of sunlight, number of trees, and tree cover (Cole et al. 2008; Cole 2013). This research illustrates the need for long-term studies that evaluate a more comprehensive array of ecological measurements; rapid assessment monitoring protocols are more likely to miss documenting potentially important long-term ecological changes occurring to ecology of campsites.

Vegetation cover and soil loss

As tree canopies thin, shade intolerant plants replace shade tolerant plants, contributing to greater compositional changes. From a visual perspective, campsites are increasingly developing a grassy "lawn-like" appearance, including the full complement of common lawn weeds (dandelion, chickweed, clover). On the positive side, campsites are increasingly colonized by more trampling resistant plants, thus protecting and retaining soils (Hammitt et al. 2014, Marion et al. 2016). The increasing dominance of graminoids on campsites is consistent with findings from other studies that demonstrate their greater resistance to trampling (Marion and Cole 1996; Marion 1984). Graminoids also have greater resilience to trampling, recovering more quickly due to their flexible stems, narrow durable leaves, and fast growth rates (Pickering 2010; Sun and Liddle 1993). However, these changes increase the unnaturalness of campsites ecologically and to visitors.

Soil loss is the most significant and irreversible long-term change occurring on BWCAW campsites. It is also a cumulative change – soil eroded by wind or water does not return unless replaced through site management actions. Our data reveal that substantial soil loss has occurred on campsites. Shoreline boat landing areas have the deepest incision and the most localized soil loss. On campsites, mean estimated soil loss is 6 cm, though aggregate soil loss is substantial due to the larger areas affected. As sites continue to erode, there will be more exposed rock and roots that will encourage visitors to create additional satellite tenting areas.

Managing for Sustainability

There are several key visitor impact management strategies and actions that managers can consider for limiting future impacts and improving the sustainability of the BWCAW campsite infrastructure. These strategies and actions are described by Cole et al. (1987) and Marion (In Press) and discussed here.

Manage Use Levels

The initial 1982 BWCAW campsite study by Marion (1984) found statistically significant relationships for eight core indicators of camping impact. Due to the curvilinear use-impact relationship the majority of impact occurs between campsite creation and moderate levels of use (20-40 nights/yr). For moderate use campsites a doubling or tripling of use contributes little additional impact because many indicators have already reached high or near-maximum impact levels. For example, organic soils and tree seedlings/saplings have already been lost and soil compaction is at near-maximum levels (Marion 1984). Reducing use to address campsite impacts would be ineffectual unless substantial use reductions were applied, to below moderate use levels. However, some forms of impact did increase significantly from moderate to high use (>60 nights/yr) campsites, including exposed soil, campsite size (Marion 1984), and from this study, soil loss. However, improvements in resource conditions would be marginal as the great majority of change for these indicators also occurs at the lower end of the spectrum of use. As will be revealed in the following sections, research consistently reveals the greater efficacy of manipulating other factors to reduce camping impacts.

Modify the Location of Use

A key issue for managing campsites sustainably is to ensure that the mean and aggregate area impacted does not increase over time (Marion In Press). Designating specific camping sites can limit informal campsite creation and ensure campsites are located in areas that inhibit site expansion over time. Toward that goal we tested the efficacy of a site expansion potential rating developed in 1984 (Table 2) that could be applied by managers when selecting sustainable campsite locations. Our non-significant findings suggest that it did not accurately predict increases to campsite size over time. In the field we observed that the presence and density of woody vegetation cover as a deterrent to campsite expansion was ephemeral, given that forest succession, wildfires, insects/diseases, wind-throw, and tree cutting by visitors can remove trees and shrubs over time. Further, we noted that satellite tenting areas were created even when only a quarter of the adjacent offsite areas were favorable to expansion. Based on these findings we refined the expansion potential rating practice as follows:

> A sustainable campsite should stay its designed size in perpetuity, bounded by adjacent offsite areas that are not conducive to tenting or other camping activities due to sloping topography or substantial rockiness. Sustainable

practice should not rely on woody vegetation as this can change over time due to forest succession, wildfires, or tree cutting. In addition, the percentage of an area within a 100 buffer around a proposed campsite boundary that would inhibit all tenting activity should be estimated. The best campsite locations should score above 85%, meaning 15% (100%-85%) of the offsite areas are sufficiently flat that tenting activity could occur there (disregarding current vegetation).

We believe that this revised rating offers an improved scale for identifying potential campsite locations that will effectively resist future expansion.

Managers also can select resistant locations and construct expansion resistant campsites to increase their impact-resistance and the spatial concentration of camping activities (Marion In Press). A relatively new method to constrain campsite expansion is to construct "side-hill" campsites within sloping terrain, ideally within landform grades in excess of 15%. Similar to side-hill trails, cut-and-fill excavation is employed to construct separate tent pads and a core cooking area (Daniels and Marion 2006, Marion and Farrell 2002). More than 800 side-hill campsites have constructed along the Appalachian Trail, including within wilderness-designated areas, and trail managers have considered them a substantial success in containing camping activity within a small footprint (citation?). An advantage is that visitors are afforded close views of pristine conditions in adjacent offsite areas. Some routine maintenance is needed to crown and smooth the tent pads and maintain supporting rockwork and access trails.

Increase Resource Resistance

The layout of existing campsites can be evaluated to meet visitor's needs and enhance their sustainability. Visitors have shown through their creation of numerous satellite tenting areas that the current layout is inadequate in some meaningful way. A social science study can aid managers by determining why visitors are creating and using satellite tenting areas. Public input can guide more effective adjustments in the layout of the campsites that meet visitors' needs while minimizing site expansion and avoidable impacts to soil and vegetation.

Based on those considerations, managers can allow informal campsite changes to continue or seek to close satellite areas, while simultaneously improving the quality of tenting areas within core campsite areas. If social attributes are a driving factor, then managers should strive for greater separation between tenting areas as they seek to construct more comfortable tent pads in the core area. If shade or privacy are important factors, then our study suggests that retaining and improving expansion-resistant satellite tenting areas may limit any increase in aggregate campsite sizes. Careful selection of locations that are resistant to soil erosion and further expansion will ensure greater sustainability under high use over time (Marion In Press).

An effective alternate practice for existing campsites is a combination of site improvement and site ruination work to deter satellite tenting areas. As shown in this study, areas that are eroded develop uneven terrain with exposed rocks and roots that deter tenting. To prevent the use of satellite areas, agency staff can bury large rocks deeply with a protruding portion that prevents tenting (Marion and Sober 1987). In the absence of large "ice-berg" rocks, managers can create uneven terrain by digging shallow depressions and mounding soil to ruin tenting spots, along with adding organic litter and plantings to naturalize the area. Simultaneously, staff needs to remove rocks, stumps, and/or add soil over roots to create several perfect tent pads within the core campsite area, practices that we observed at a number of our BWCAW study campsites. However, we recognize that funding constraints limit the use of this strategy.

Other effective site management actions include anchoring fire grates or rings to attract and spatially concentrate trampling intensive activities such as cooking. Many BWCAW fire grates have been anchored directly on highly resistant bedrock to shift traffic away from more vulnerable vegetation and soil. Rockwork around tent pads and on steep campsite access trails also can limit soil erosion. Some campsites have multiple boat landings and our data reveal that these locations are particularly prone to substantial soil loss. Limiting the number of landings, selecting new sites with bedrock landings, or hardening existing landings with subtle naturally-appearing rockwork can limit the amount of soil loss. Managers also can fell large trees or move large rocks onto unnecessary landings to close them.

Soil loss also can be limited by increasing ground vegetation cover. This study demonstrated that as campsites lose their trees, the increased sunlight allows an expansion of resistant graminoid cover in peripheral areas. This trend will undoubtedly continue unless effective actions are implemented to discourage or prevent tree damage and felling. Fortunately, increased ground vegetation cover helps reduce soil loss. Seeding the sunniest portions of campsites with native grasses can accelerate the trends toward increasing campsite plant cover, which should retard additional campsite soil loss. However, we acknowledge that this action would add to the unnatural appearance of campsites. Alternately, managers could seek to restore the natural appearance of the campsites by planting tree seedlings in protected locations on campsites, such as close to large rocks or in small protected patches of existing vegetation. Protective temporary fencing may also be necessary. Our study results suggest that this practice will be unsuccessful unless the current high rate of tree felling for firewood can be effectively halted.

Modify Visitor Behavior

The USFS provides Leave No Trace (LNT) messaging as part of its permitting process to convey and encourage the adoption of low impact camping practices. A BWCAW Trip Planning Guide currently addresses tree-cutting impacts by asking visitors to: 1) substitute a camp stove for a campfire to cook meals, 2) burn only small diameter dead wood found lying on the ground, 3) collect firewood away from campsites by paddling down the shore and walking into the woods, and 4) collect wood that is easily broken by hand or cut with a small folding saw to eliminate the need for an axe. (In addition, cutting live vegetation for any reason is illegal, although we counted 1054 tree stumps on 81 campsites during our 2014 field work.) The efficacy of educational messaging would be enhanced if this information were conveyed effectively, including through concessionaires, along with a compelling rationale so that visitors will remember and follow the guidance when camping (Marion and Reid 2007). Other actions to curb the harvesting of live trees for firewood is to ask visitors to leave all woods tools (axe, hatchet, saw) at home, or to prohibit woods tools within the wilderness except for trail and campsite maintenance activities.

Close and Rehabilitate the Resource

Closing highly impacted campsites and replacing them with new sites is generally an ineffective strategy unless: 1) the new sites are considerably more impact-resistant then the closed sites, and 2) recovery of sites is likely with a reasonable assurance that continued use of the closed sites can be prevented (Hall 2001, Cole and Ranz 1983). Practitioners know that it’s difficult to close a campsite because people who have been coming to the area for years know where it is and may continue to use it. Felling large trees over the boat landings and tenting areas appears to be an effective management practice based on our observations of closed campsites. Plantings of trees on these sites also appeared to have high survivorship.

Campsite closure is easier in the BWCAW than in other wilderness areas because camping is restricted to designated campsites; extracting the fire grates and toilets effectively communicates that the campsite is no longer legal to use. Visitor compliance is generally good regarding overnight use of closed campsites, though day use activities are not prohibited. We were able to positively relocate and survey 12 campsites in 2014 that had been closed between 31-45 years. Four campsites had recovered to the point that they were indistinguishable from the surrounding forest and recovery was substantial on five campsites. Portions of three closed campsites were not recovering due to continued day use activity, primarily as lunch stops.

While the USFS has sought to sustainably manage designated campsites for long-term use, this study reveals that some impacts continue to degrade over time, particularly tree and soil loss. While some management actions may be effective in slowing or reversing these impacts they do present a long-term management dilemma. One option available to managers is to close campsites that reach unacceptable levels of impact that cannot be easily reversed and replace them with new more sustainable campsites. Our observations on closed campsites suggest that substantial recovery to near-natural conditions can occur on closed sites in two to three decades so this could be a viable long-term campsite management practice.

Conclusion

To preserve wilderness in perpetuity while providing recreation opportunities, wilderness managers need to consider potential impacts over not one year or ten years, but over decades and centuries. The results of this study document long-term changes and trends in resource conditions on a large sample of wilderness campsites. The campsite condition over 32 years has changed significantly. While the total area of the campsites has remained similar, expansion into peripheral areas has occurred while core areas have contracted. Both the area of exposed soil and area of vegetation cover increased over time due to the complexities of the visitor use and altered sunlight patterns. Trees continue to be harvested by visitors for firewood, causing campsites to lose tree cover and gain graminoid cover. Where trampling-resistant vegetation has been unable to establish, sites are losing substantial amounts of soil. Results from this study quantify these long-term changes and suggest effective sustainable management prescriptions for the BWCAW and other areas that employ designated site camping.

By focusing greater attention on sustainable campsite management, agency staff can prolong the period of time that campsites can accommodate visitation and remain in good condition. We suggest that this should involve a combination of actions that include selecting resistant locations that preclude or hinder expansion, construction of side-hill campsites or of tent pads that will attract and spatially concentrate use and impact, maintenance of sites to reduce soil loss, and education, and regulation of visitors to encourage the learning and adoption of low impact camping practices. While agency funding and staffing constraints often limit the ability of field staff to accomplish these tasks, we suggest that intensive visitor use will demand intensive site and visitor management if wilderness managers are to accomplish their dual mission of preserving wilderness ecosystems while accommodating ample opportunities for high quality recreational visits.

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CHAPTER 3: "NATURALNESS" IN BOUNDARY WATERS CANOE AREA WILDERNESS, MN: CAMPING AND NON-NATIVE PLANT ECOLOGY

Abstract

Wilderness areas in the United States are preserved for their untrammeled naturalness and opportunities for unconfined recreation, and under the Wilderness Act amendments in 1984, federal agencies are required to monitor wilderness quality over time. The Boundary Waters Canoe Area Wilderness has these qualities but long-term recreation visitation pressures on campsites can cause significant ecological changes. Canoeing and camping in the BWCAW are historical uses. This paper explores ecological changes on campsites, specifically looking at non-native plant ecology over three decades. The study replicates work done in 1982 analyzing ground cover, tree cover, non-native plant abundance and cover, and species richness at nodal campsites as well as on paired controls. Camping pressure has removed substantial tree and shrub cover on campsites and replaced forbs with graminoids, altering the perceived wilderness character on these sites.

Non-native species such as *Trifolium repens, Taraxacum officinale* and *Plantago major*, common backyard weeds, are prevalent but restricted to the campsites. Over the span of thirty-two years, the total number of non-native plant species found on campsites has not risen, though their mean relative cover has increased significantly. In addition, non-native plants present in 1982 have spread to more campsites over time. Of the 23 non-native herbs and grasses currently found at the campsites, only *Cirsium arvense* is considered a noxious weed by the state of Minnesota and thus a threat to wilderness quality.

Other, non-invasive, non-native plants fall into a grey area in the context of the "naturalness" in an area protected under the Wilderness Act, since they may provide ecological services even as they alter its wilderness character. Moreover, managing such non-native plants would mean exerting human control over the landscape. Wilderness managers thus face a difficult challenge in coping with the long-term impacts of camping and canoeing on wilderness character.

Keywords: wilderness character, non-native plants, recreation ecology, campsite management, long-term changes

Introduction

The Wilderness Act of 1964 established the National Wilderness Preservation System, which has grown to include nearly 110 million acres, accounting for 17% of all federally owned public land and 5% of the entire U.S. Under this legislation, managers are to preserve natural ecosystems where “the earth and its community of life are untrammeled by man” and “opportunities for solitude or a primitive and unconfined type of recreation” abound, allowing for the land’s preservation and use in an unimpaired condition for future enjoyment. Wilderness management emphasizes natural stewardship, where a hands-off approach allows for the forces of nature to prevail in order to reduce unintended consequences of environmental management (Hendee and Dawson 2002). The hands-off approach becomes problematic when wilderness areas receive heavy recreational visitation, which can cause resource impacts that threaten their environmental integrity. As the use of a wilderness area increases, impacts accumulate and managers are forced to construct or actively manage trails and campsites, or increase regulation and education to minimize impacts.

Threats to wilderness are defined as anything that creates negative impacts to the wilderness condition and values. Recreation visitation is a threat due to the adverse ecological effects caused by it or done by managers to accommodate it. The introduction and dispersal of non-native plants in wilderness pose a threat because they have direct and indirect ecosystem effects that compromise ecological integrity (Randall 2000). One definition of ecological integrity is an ecosystem that is whole and unimpaired, with characteristics including: 1) a full complement of native species, 2) viable indicator species, 3) intact trophic levels, 4) biological communities of mixed age classes, 5) balanced productivity and decomposition rates and 6) ecosystem resistance and resilience to a changing climate (Cole and Yung 2010). Recreation visitation and non-native plant invasions are intertwined in protected natural areas because many non-native plants are introduced and dispersed by visitors, where they reside primarily on trails and recreation sites (Morgan and Carnegie 2009; Pickering and Hill 2007).

One of the tenets of the Wilderness Act is to manage for “naturalness”, but the meaning of “naturalness” remains open to interpretation. It can mean an ecosystem lacking intentional human control, or a pristine system free of human effects. Conversely, “naturalness” also can entail a situation in which managers actively maintain the historical condition of an ecosystem (Cole and Yung 2010). The role of non-native plants in wilderness areas reflects this ambiguity.

These plants are generally unintentionally introduced and spread by wilderness visitors as seeds attach to their gear or clothing, and thus the ecosystem has traces of human effect when non-natives are present (Marion et al. 1986). The presence of non-native plants on campsites is troubling in terms of the visitor experience as well. Visitors see dandelion (*Taraxacum officinale*), plantain (*Plantago spp*.) and clover (*Trifolium spp*.), common in suburban lawn species, on campsites and trails. Since visitors spend the majority of their time on developed campsites or trails, they may believe encountering these suburban lawn species is the norm for wilderness vegetation (Marion et al. 1986).

Non-native invaders tend to have traits that enable them to out-compete native plants, including fast growth rates, high seed production and adaptability to a wide range of environments (Alpert 2006; Van Kleunen et al. 2010; Alpert et al. 2000; Pysek and Richardson 2010). Dispersal opportunities occur when visitation is concentrated in remote areas, such as at campsites or along trails, and propagules can spread via clothing and equipment (Whinam et al. 2005; Pickering and Mount 2010). Seeds on the clothing of hikers can be carried as far as 13km on average (Ansong and Pickering 2014). Many non-native species are dispersed along disturbed areas where visitors frequent, and their range does not extend much past the disturbed trail or recreation site border. Morgan and Carnegie (2009) found 32 non-natives specie within 100m of backcountry huts in the subalpine area. Across national parks in Australia, non-natives species were recorded within 20m of the trail edge, with a rapid decrease in abundance occurring with increasing distance (Ngugi et al. 2014). This pattern was also observed along portage trails in the Boundary Waters Canoe Area Wilderness (Dickens et al. 2005).

Non-native plants can invade and displace other native species altering system productivity, diversity and stability. Non-native plants can fill a niche and linger in the landscape after a disturbance event has occurred (Ahlgren and Algren 1984). Marion (1984) found that even after a decade of closure, pre-existing campsites still maintain a non-native plant community, with non-natives accounting for an average of 20% cover on campsites. Of particular concern, is when non-native species are found in un-disturbed areas. Barros and Pickering (2014) reported that *Taraxacum officinale*, a common "disturbance-associated" non-native species, was found to have spread from a recreation site to undisturbed locations.

Land managers are increasingly conducting comprehensive inventories identifying the presence, distribution, frequency and cover of non-natives. Many land management agencies are developing policies and actions to control non-native plants and prevent new invasions to address the threats they pose to wilderness areas (Randall 2000; Cole and Landres 1996).

The Boundary Waters Canoe Area Wilderness (BWCAW) is a U.S. Forest Service (USFS) managed 1,090,000-acre wilderness area in northeastern Minnesota with over 1000 lakes. Visitors have canoed, portaged and camped throughout this area for many decades and managers seek to perpetuate this traditional and historical mode of recreation (Landres et al. 2015). There are approximately 80 entry points, 18 hiking trails and 1200 miles of canoe trails in the BWCAW. The area receives over 250,000 visitors annually and the USFS restricts use through a permit season with entry point quotas. A central challenge for BWCAW management is interpreting the meanings of naturalness and untrammeled nature for a wilderness where canoeing and camping traditions are an inextricable part of the area's historical and cultural values.

The USFS maintains over 2,000 campsites in the BWCAW, each with a primitive pit toilet and steel fire grate. A core objective is to manage these long-term designated campsites to maintain their natural conditions and limit resource impacts. The purpose of this study is to examine long-term trends for non-native plants on a large sample of BWCAW campsites over a 32 year period. Objectives include: 1) evaluate how the ecology of campsites has changed over time, 2) quantify long-term changes in species richness and non-native plants on campsites and undisturbed control areas, and 3) investigate the BWCAW qualities of wilderness character given the long-term human-environment interactions.

Study Area and Methods

The study examined 81 campsites within the USFS Kawishiwi District of the Superior National Forest located near Ely, MN. Study area soils are derived from glacial deposits, covering a thin mantle of glacial-till and lacustrine sediments (Prettyman 1987). The area receives between 66 and 78 cm of precipitation per year, with 40% falling as snow. The average summer temperature is 20^{o} C and the average winter temperature is -11^{o} C. Primary plant communities include the jack pine forest *(Pinus banksiana Lambert)* associated with red pine *Pinus resinosa* and white oak *Quercus alba L.;* the Great Lakes pine forest dominated by white pine (*Pinus strobus L*.) and red pine (*Pinus resinosa Aiton)* associated with paper birch (Betula papyrifera Marshall); and the northern boreal hardwood-conifer forest dominated by big-toothed aspen *Populus tremuloides,* paper birch *Betuala papyrifera,* balsam fir *(Abies balsamea L.),* white spruce *(Picea glauca Moench),* and northern white pine *(Thuja occidentalis L.)* (Moyle and Moyle 1977).

This study replicates Marion's 1982 recreation ecology doctoral study of 96 wilderness campsites and paired control areas (Marion 1984). Sites were selected through stratified random sample, where sites were equally distributed among three use levels and five ecological land types. Since that time, ten campsites have been closed and five were omitted because their ecology was substantially altered by wind-throw or wildfire. Each shoreline campsite is accessed by boat and includes a boat landing area, fire grate, tenting areas, and an open-air pit toilet located inland and accessed by trail. On many campsites visitors have also created satellite tenting spots located adjacent to the campsites that are not maintained by USFS staff.

At each campsite, a circular control plot of $50m^2$ (size determined based on species area curve from nested plot technique) was also assessed in a nearby undisturbed area. Each control plot was environmentally similar to the campsite it was paired with; it had the same soil type, ecological land type, aspect, slope, soil depth to bedrock, and distance to water. Eighty-one sites from the original 1982 study were re-measured in 2014 using the same protocols. Resource conditions that were measured in the original study include plant diversity and abundance, ground cover, and vegetation composition.

Vegetation sampling was completed using a modified quadrat method with whole-area determinations for the campsites and controls. Campsite measures included areas of any adjacent satellite tenting spots and excluded any internal pockets of undisturbed vegetation. Plants were identified to the species and their cover estimates were recorded as: 1 = Solitary, 0.5% cover, 2 = Few plants, 1% cover, 3 = Numerous, with cover 2-5%; 4 = Cover 6-25%; 5 = Cover 26-50%; 6 = Cover 51-75%; and 7 = Cover >75% (after Braun-Blanquet, 1965). Trees and seedlings on campsites were tallied. These numbers were divided by the individual campsite size to obtain a tree per hectare metric. Coverage values were aggregated by growth habit to obtain campsite cover estimates for tree, shrub, herbaceous, and grass cover. Coverage estimates were assessed for bare soil, exposed bedrock, organic litter, sparse vegetation (5-50% plant cover), and dense vegetation (51-100% plant cover). Relative cover for plants was determined by dividing the species coverage by the percent of ground vegetation cover for each campsite. Areal coverage in square meters of each plant species was also determined on campsites by multiplying the percent cover by campsite size. Areal measures of vegetation loss and exposed soil were calculated by using the percent cover estimates and multiplying them by campsite size. In 2014, estimates of total soil loss on the campsites and canoe landings were also included.

Longitudinal 1982 to 2014 comparisons were made and statistically analyzed with paired t-tests of campsite-to-campsite and control-to-control measurements. To examine current recreation activity impacts the 2014 campsite values were compared to their paired control values using paired t-tests. An ANOVA was applied to investigate the relative influence of tree cover on vegetative indicators. SAS JMP software was used for all statistical testing.

Results

Divergence between ecology on campsite and control

Open and active use of the campsites over thirty-two years has caused a marked divergence in the ecology on the campsites compared to surrounding control areas. In 1982, it was clear that campsites and controls had a different vegetation cover. The data reveals that campsites become increasingly altered over time and do not reflect the same shift in vegetation structure occurring in the surrounding forests. Control areas experienced a significant decrease in herbaceous and grass cover and an increase in tree and moss cover. Over the thirty-two year measurement period, the native forest matured (Figure 3.1). Trees grew, canopy coverage extended, the forest floor received less light, shading out forbs and grasses while mosses expanded. While the control gained tree cover and lost grass cover, campsites experienced the opposite. Campsites are operating under a disturbed regime and over time have become more disparate from the control sites in vegetation structure and cover.

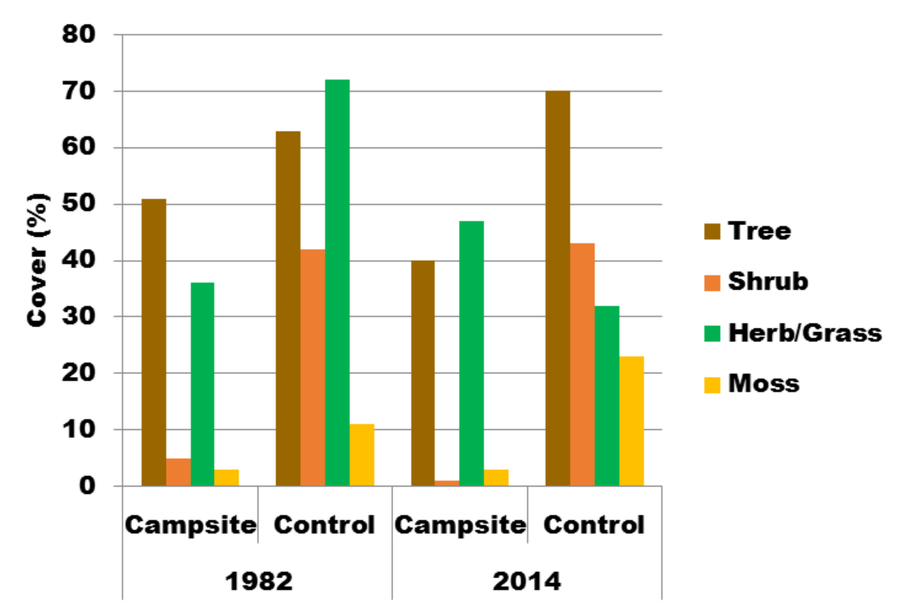

Figure 3.1. Vegetation cover on campsite and control areas from 1982 to 2014.

From 1982 to 2014, tree cover has reduced significantly on campsites. Figure 1 shows mean tree cover on campsites declined by 10.5% from 1982 to 2014 (p =.004). Tree regeneration is threatened by harvesting of trees by visitors for firewood, 65 trees/ha (p =.031) were lost on campsites from 1982 to 2014 (Eagleston and Marion, Draft). Loss of tree cover and tree regeneration has led to an increase of sunlight on campsites. Loss of tree cover and opening of the canopy has allowed herbaceous and graminoid species to thrive on campsites, increasing in cover from 36.2% to 46.5% over 32 years (p = .019).

There are environmental dynamics associated with a loss in tree cover. The amount of tree cover was measured using categories of percent cover. Using an ANOVA, the categories recorded were grouped into three classes of tree cover: low (0-25%), medium (26-50%), and high (51-100%). Looking at 2014 data for tree cover, sites with lower tree cover experience higher species richness and the average number of non-native plants per site is higher (Table 1). The trend in higher species diversity with low tree cover is seen over time as well, with campsites in 2014 showing 4.9 ± 2.6 more species per site than in 1982 (p = .032).

Table 3.1. Effect of tree cover on plant abundance and cover on campsites in 2014

Indicator	Tree cover			F-ratio	P-value
	Low (n=27)	Medium (n=23)	High (n=31)		
Species Richness	17.85 (± 4.9)	16.5 (±3.3)	14.6 (±3.9)	4.41	.015
Number of Non-natives	5 (±2.0)	4.3 (±2.1)	2.9 (±4.5)	8.01	<.001
Relative cover of Non-natives	3.1 (±2.0)	7.4 (±20.4)	2.8 (±2.5)	1.37	.260

The increase in number of species on campsites in 2014 carries over to the number of non-native species found on campsites. Interestingly, the total number of non-native plants found on BWCAW campsites has remained the same at 21, though the average number of non-native plants per site has risen from 1.8 to 4.0 (Table 3.2). Over 32 years, non-native plants have had time to migrate to more campsites. Figure 2 shows a map of which campsites gained and lost non-native species. Non-natives are found on 91.4% of campsites, up from 67.9% in 1982, i.e., the number of campsites with non-native plants increased from 55 to 74; whereas on the control, non-native plants were found on only 3 more sites in 2014 compared to 1982.

Table 3.2. Non-native species abundance in BWCAW

Indicator	2014		1982		Mean Difference 2014 Camp - 1982 Camp	P-Value
	Camp	Control	Camp	Control		
Non-native species (total #)	21	3	21	0	0	--
Non-native species/site (#)	4.0	0.04	1.8	0	2.2 (±0.3)	<.001
Sites with non-natives species (%)	91.4	3.7	67.9	0	23.5	--
Mean plant cover/site (%)	7.9	0.03	11.2	0	-3.3 (±2.7)	.211
Mean relative cover of non-natives/site (%)	16.1	0.05	21.7	0	-5.6 (±4.5)	.212

While the number of non-native plant species has increased with time, the relative cover has not. As shown in Table 3.2, neither the mean cover nor relative cover of non-native species changed significantly from 1982 to 2014. The mean cover is the average cover estimate of non-natives for the site; the relative cover adjusts the cover class assigned to the non-native species to the amount of vegetation cover present on the site. The relative cover in 2014 is not significantly different from the relative cover of non-native species in 1982 (p = .212).

Changes in non-native cover and abundance at species level

Ongoing use of the campsites creates a disturbed environment where vegetation is trampled, leaves are pulverized and organic litter is lost, and the underlying soil is exposed (Marion et al. 2016). Ground cover composition changed from 1982 to 2014 with a loss by 15.4% in organic litter, 8.2% increase in exposed soil, and a 16.8% increase in vegetation cover. This trend can be explained by conflicting mechanisms of trampling pressure removing fragile herbaceous vegetation while trampling-resistant species, primarily graminoids (grasses and sedges) increased in cover. Graminoids have been shown to be highly resistant and resilient to trampling pressures (Cole 1995a), though they are generally shade-intolerant. Coupled with loss of tree cover and greater sunlight, graminoids are able to colonize less trafficked peripheral areas and/or replace native plants. Hence, campsites have increased vegetation cover in 2014.

Non-native plants are also present on campsites and are generally more competitive under disturbed conditions than native plants. They also benefit from increased sunlight, however, but they are less trampling resistant than graminoids. Table 3.3 shows the change in relative cover for each non-native species from 1982 to 2014. Many species lost relative cover in 2014, the top ones including: *Trifolium repens, Agrostis alba*, *Festuca rubra*, *Phleum pratense* and *Plantago major*. Other species expanded in relative cover values, *Bromis inermis* gained by 39.9%. Some species were found at more campsites but their areal cover in square meters did not change appreciably from 1982 to 2014 (Table 3.3). For example, *Taraxacum officinale* declined from 79% to 36.5% of the campsites from 2014 to 1982, while relative cover declined 4.9% and areal cover decreased by 48.5m^2.

Of the non-native species found in BWCAW, the expansion of plants classified as noxious weeds are of particular concern. *Cirsium arvense* is a prohibited noxious weed in the state of Minnesota and is actively controlled by USFS staff (Alexander et al. 2013). While the relative cover decreased from 1982 to 2014, its areal coverage on 81 campsites increased by 8.6m^2. *Cirsium arvense* was found on one campsite in 1982 and in 2014 it was found on six campsites. Figure 3 shows the spatial pattern of the expansion of *Cirsium arvense. Cirsium arvense* expanded to campsites on lakes up to 23km away. It is likely that the population on the campsite in 1982 was the source for introductions to other campsites in 2014, but rather that people visiting the campsites throughout the BWCA introduced them. *Hieracium aurantiacum* and *Hieracium caespitosum* are both rated as having potential to cause moderate ecological damage and are on the watch list for USFS (Alexander et al. 2013). *Hieracium caespitosum* was not found at all in 1982 but in 2014 covered 51m^2 on the 81 sites measured, and was found on 19.8% of the campsites. *Hieracium aurantiacum* increased in relative cover in 2014, was found on 11.1% of campsites in 2014 and covered 83.6 m^2 on the campsites measured.

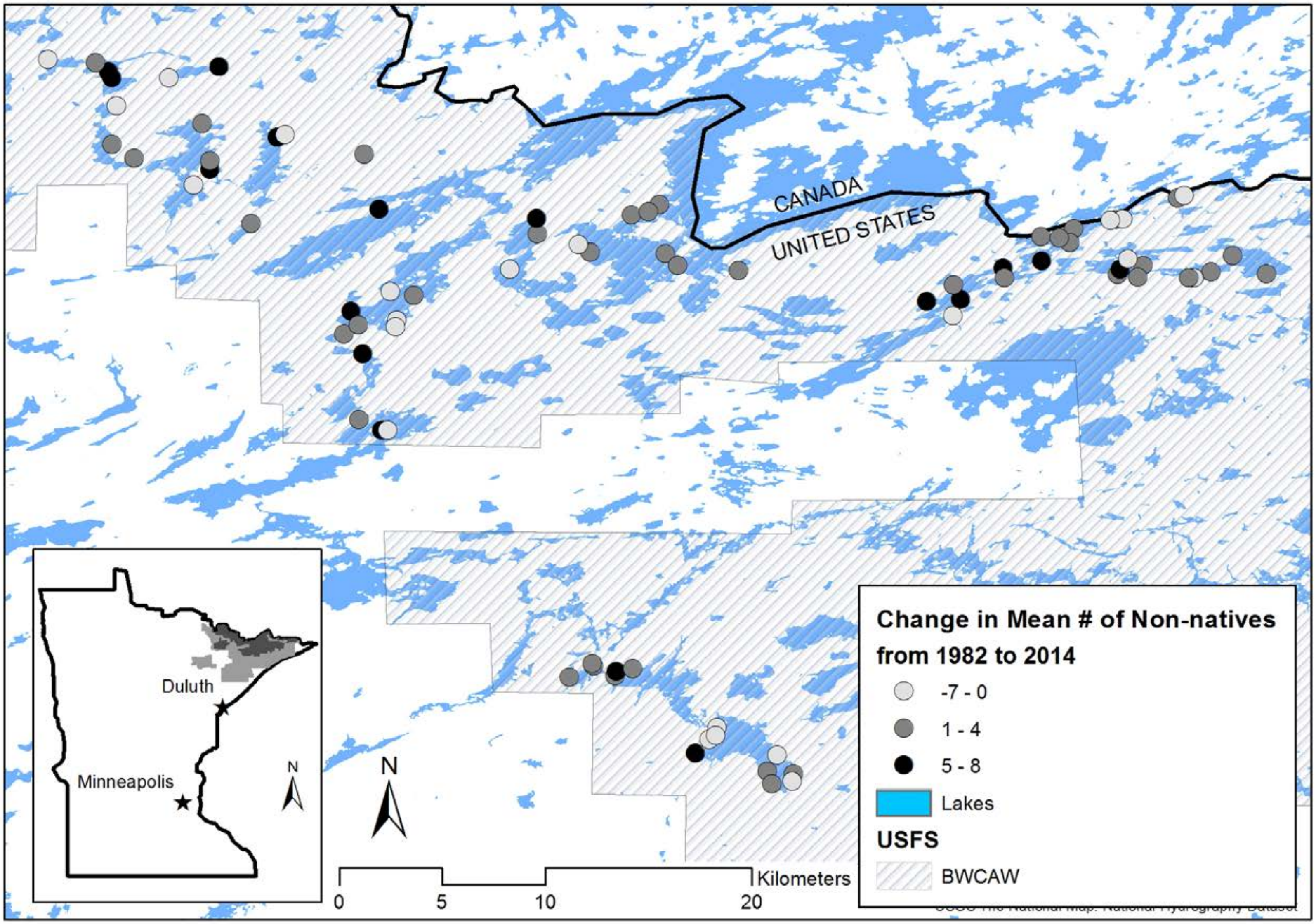

Figure 3.2. Map illustrating changes in mean number of non-native plants found on BWCAW campsites from 1986 to 2014.

Table 3.3. Cover and frequency of non-native species

Non-native Plant Species	Relative Cover (%) 1982	Relative Cover (%) 2014	Difference in Relative Cover	Present on campsites (%) 1982	Present on campsites (%) 2014	Presence Difference (%)	Sum Areal Cover (m^2) 1982	Sum Areal Cover (m^2) 2014	Difference in Areal Cover (m^2)
Herbs									
Achillea millefolium	2.5	1.4	-1.2	7.3	13.6	6.3	19.3	19.3	0.0
Capsella bursa-pastoris	3.1	1.2	-1.9	4.2	11.1	6.9	19.1	15.6	-3.5
Cerastium vulgatum	6.3	1.8	-4.5	25.0	38.3	13.3	105.3	66.6	-38.7
*Chenopodium album**	3.5	--	-3.5	1.0	--	-1.0	0.0	0.0	0.0
Chrysanthemum leucanthemum	2.3	3.5	1.2	3.1	23.5	20.3	10.4	77.4	67.0
Cirsium arvense #	5.0	1.3	-3.7	2.1	7.4	5.3	2.9	11.5	8.6
Hieracium aurantiacum	0.8	6.0	5.2	2.1	11.1	9.0	1.6	85.2	83.6
*Hieracium caespitosum***	--	2.2	2.2	--	19.8	19.8	0.0	51.5	51.5
Plantago major	11.1	3.5	-7.6	38.5	72.8	34.3	347.6	291.5	-56.1
Polygonum aviculare	1.1	0.8	-0.3	1.0	6.2	5.1	0.0	6.4	6.4
Prunella vulgaris	3.3	2.4	-0.9	3.1	7.4	4.3	5.0	9.1	4.1
Ranunculus acris	1.2	1.8	0.6	1.0	3.7	2.7	0.0	7.3	7.3
*Rumex acetosella***	--	3.8	3.8	--	1.2	1.2	0.0	12.1	12.1
Taraxacum officinale	7.7	2.8	-4.9	36.5	79.0	42.6	276.1	227.6	-48.5
*Trifolium aureum ***	0.0	1.6	1.6	--	3.7	3.7	0.0	5.2	5.2
Trifolium pratense	4.6	1.6	-3.0	5.2	2.5	-2.7	17.7	12.8	-4.9
Trifolium procumbens	1.1	4.7	3.5	1.0	2.5	1.4	0.9	577.6	576.6
Trifolium repens	20.8	8.5	-12.3	38.5	63.0	24.4	699.3	10.9	-688.4
Grasses									
Agropyron repens	8.5	2.5	-6.0	6.3	6.2	-0.1	21.6	17.1	-4.4
Agrostis alba	20.2	1.4	-18.8	2.1	1.2	-0.8	84.4	0.7	-83.7
Bromis inermis	1.3	41.1	39.9	2.1	3.7	1.6	2.6	62.6	60.0
*Festuca rubra**	10.4	--	-10.4	2.1	--	-2.1	36.8	0.0	-36.8
Phleum pratense	9.5	3.2	-6.4	27.1	21.0	-6.1	333.6	68.8	-264.7
Mean			-1.03	9.7	19.0	9.3	86.3	71.2	-15.1
St Error			2.61			2.9			42.3
P-value			**.349**			**.003**			**.362**

*only found in 1982
**only found in 2014
invasive

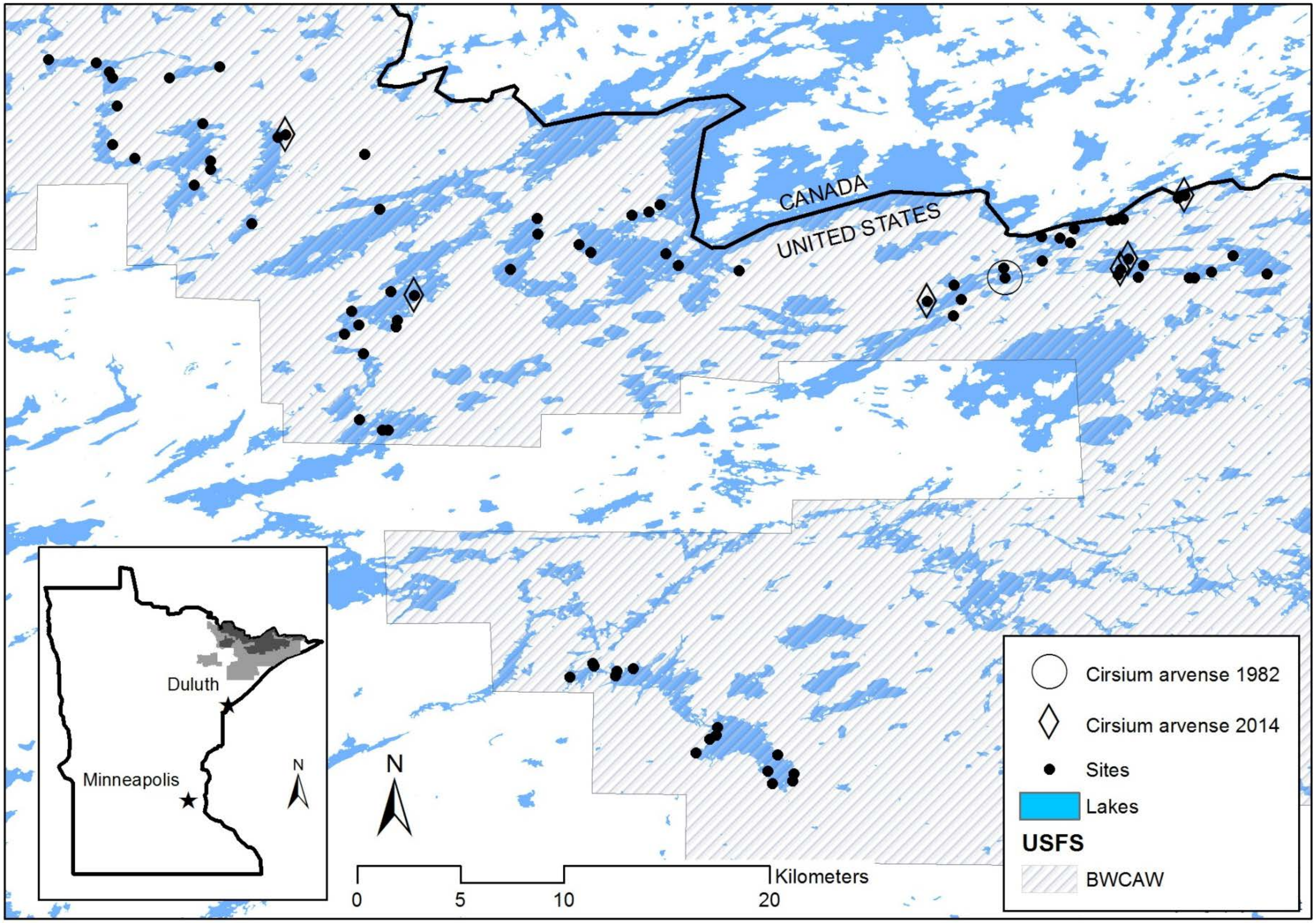

Figure 3.3. Movement of *Cirsium arvense* on study campsites from 1982 to 2014.

Discussion

Are non-natives in the BWCAW an ecological threat?

While non-native species are not desirable, for non-natives to be truly detrimental, it must be clear that they show harm to the environment, which can be difficult to define (Sagoff 2005). Loss of species richness, alteration of biogeochemical processes in the environment, and undermining ecological integrity are all viable causes of environmental harm (Callaway and Aschehoug 2000; Pysek et al. 2004). Non-native species that are considered harmful have been defined as "invasive," particularly those that spread easily and outcompete native plants, but not all non-native species are invasive (Ricciardi and Cohen 2007). Invasive species, once transported to an area, are self-sustaining and establish in an area, become naturalized to the location they have invaded, have the potential to spread over large distances and cause impact to the economy, environment or health (Richardson et al. 2011).

Only one of the twenty-one non-native species found in BWCAW campsites is considered noxious. The Minnesota Noxious Weed Law (MN Statutes 18.75-18.91) defines noxious weed as any plant that is injurious to public health or to the environment. The Minnesota Department of Agriculture lists Canada thistle, *Cirsium arvense,* as a prohibited weed and calls for the control of maturation and spread of propagating parts. The cover of *Cirsium arvense*, increased by 8.6m^2 on the 81 campsites from 1982 to 2014. It has not been found in off-site control areas.

The other non-natives found at the BWCAW campsites are not on the noxious weed list. To become invasive, the species goes through four stages of invasion: transport, colonization, establishment and landscape spread (Theoharides and Dukes, 2007). Under the Ten's Rule, only 10% of species are dispersed to new areas, of those only 10% of species become established, and 10% of those species actually spread and invade an area (Williamson and Fitte, 1996). Propagule pressure is the leading factor of why some plants are able to quickly establish in an area and become invasive while others are not (Colautti et al., 2006). We are not seeing non-natives become invasive in surrounding control areas. Aside from *Cirsium arvense,* the non-natives found in the BWCAW are not causing ecological harm. Non-natives are rarely present in control areas, with only 3 of the 81 paired control areas having any non-natives and cover was at trace levels for each. Many of the non-natives found on campsites, such as dandelion (*Taraxacum officinale*) and clover (*Trifolium repens*), are shade intolerant, they do best in sunny, disturbed settings. Tree cover has been reduced on campsites over 32 years while the control areas have experienced an increase in tree cover as the forest has matured. The non-native forbs and grasses found on campsites simply are not able to survive in the shady areas surrounding the campsites.

We are not seeing non-natives become invasive on the campsites themselves. In 2014, 16.1% of the vegetation cover found on campsites were non-natives, and this proportion has fallen from 21.7% since 1982 (Table 3.2). Trampling pressure from visitors is likely the predominant factor limiting the cover of these species, though competition from grass cover may also be a factor.

While the cover of non-native species has not changed dramatically, we did see an increase in the mean number of non-native plants species per campsite from 1982 to 2014. The non-native species that had the greatest extent (were found at the most campsites) was *Plantago major*, *Taraxacum officinale* and *Trifolium repens*. This was true for both years. These are common lawn weeds that visitors are likely introducing or dispersing from campsite to campsite as seeds on their tents, gear, clothing, or footwear (Pickering and Mount 2010). Figure 2 shows that there is not a clear spatial pattern in the change of mean number of non-natives found per campsite. As a Leave No Trace practice, visitors can shake out their gear and check their clothing and shoes to remove seeds prior to outdoor trips and before leaving campsites.

Non-native plants may also provide some benefits or ecosystem services by protecting wilderness campsites from soil loss. The erosion of soil from campsites is a substantial and irreversible form of recreation-related impact. Mean soil loss on 2014 campsites was estimated at 17.2 m^3 in 2014. Even with the increase in herbaceous and graminoid cover in 2014, the typical campsite had 8.3% more exposed soil than in 1982 (p <.001). Non-natives made up 16.1% of the vegetation cover, and without them, soil loss may have been greater. Efforts to eradicate non-natives from campsites would reduce campsite vegetation cover, which aids in binding the soil and lessening water and wind soil loss. Non-native plants may continue to establish and fill in bare ground on campsites, which could further limit soil erosion on campsites.

Management of non-native plants in the context of Wilderness

The Wilderness Act describes the goal of maintaining the natural and untrammeled quality of wilderness areas since their establishment. From this study, it is clear that the ecology on campsites has markedly changed from when the Wilderness was established to now. What is not clear is whether these changes constitute trammeling or degradation in the natural quality of the BWCAW, which was established with the cultural heritage of canoeing and camping. In the context of non-native plants, managers are faced with the dilemma of whether to remove species which do not belong there or leaving them there because they provide useful ecological services that enables continued use of campsites.

The meaning of “untrammeled” in the Wilderness Act has been discussed at length. The idea of Wilderness is to have areas that are allowed to operate without the forces of man’s manipulation (Zahniser 1963). As Lucas (1973) puts it, if the ecological processes are uncontrolled then the results are desirable. If we forego the notion that recreation sites are “sacrifice sites” and uphold these areas to the same standards as the rest of the wilderness, then in the context of BWCAW, there are two actions that should be considered a “manipulation”. One is the presence of non-natives, and the other is the loss of tree cover. Non-natives were originally introduced from the logging era from horse and mule feed (Marion 1984). There were also cabins within the area before it became a federally designated Wilderness. These structures were removed, but the plants persisted with the average number of non-natives being higher on campsites that were originally logging camps or resort sites (Marion 1984). The number of non-native species did not change from 1982 to 2014. The relative cover of non-native plants on campsites also did not significantly change from 1982 to 2014. What did change was the mean number of non-native species found on each campsite. This indicates that non-natives have become more prolific throughout the wilderness as more species were found at each campsite. While non-natives have become more prevalent on each campsite, there is little evidence that they are able to disperse into undisturbed forested offsite plant communities. This is important because non-native populations are restricted to nodal areas where camping occurs, thus these species do not pose a large-scale ecological threat to the Wilderness as they are not able to establish on a landscape-level scale.

The other “manipulation” is the loss of tree cover that has occurred on campsites sites, largely due to the continued cutting of trees for firewood. Camping introduces disturbance pressure on woody vegetation both from initial use and impact when most of the tree seedlings, saplings and shrubs are lost, and later annual use over decades when mature trees are slowly lost from damage, felling, and root exposure. Managers have done limited planting of native trees on campsites in an effort to replace lost campsite trees. However, with staffing levels at record lows, trampling pressures, and visitors continuing to fell trees for firewood, the long-term success of replacing trees on campsites is low. Tree regeneration on campsites rarely occurs, though sometimes new tree or shrub seedlings can survive and mature when located in undisturbed pockets of vegetation protected from traffic by rocks or a grouping of mature trees.

Furthermore, to the extent that it were successful, there would be less sunlight to support the graminoids and non-native plants that are helping to reduce campsite soil loss.

Hendee and Dawson (2002) make the point that wilderness management is an intellectual dilemma where we try not to influence wilderness but the more people learn about it, visit it and manage it, the less wild it becomes. Wilderness is a state of mind defined by human perception, and thus wilderness does not need to be managed although people do. Under this doctrine, non-native plants are not so much a problem that needs to be managed on the land, but rather a problem that needs to be addressed with visitors. Recreationists are the main vector for the spread of non-native plants from campsite to campsite and they are the ones who need to be aware of what they are doing. More active measures could be taken to minimize the further spread of noxious weeds throughout BWCAW campsites. Leave No Trace practices can address both the inspection and removal of seeds from gear, clothing, and footwear and can also promote firewood gathering practices that do not involve woods tools and felling or cutting trees. Otherwise campsites will become more open and sunny, contrasting strongly with the undisturbed forest surrounding the sites.

We suggest that the continued loss of campsite trees strongly diminishes the perceived "naturalness" of campsites. Managers will need to deliberate the acceptability of long-term tree loss on campsites and either accept it, enhance their tree-planting and protection efforts on campsites, or implement a campsite closure and replacement program when a campsite loses most of its trees. Further, while efforts should be taken to stop spread of invasive species, we suggest that managers consider accepting presence of non-invasive non-native plants on campsites. They are not dispersing offsite and their presence provides greenery that lessens soil loss. The new standard of what is natural embraces the idea of "novel" ecosystems (Schlaepfer et al. 2011) that recognizes human interaction with the environment has occurred for many years and being a part of the ecosystem ourselves, by interacting with it, we change it irrevocably. If we embrace the concept of novel ecosystems, and accept them in the context of "naturalness" and "untrammeled" in Wilderness areas, we could have ecosystems with higher functionality and higher resiliency to work in concert with human disturbance.

Conclusion

Management of non-native plants poses a dilemma to the values associated with wilderness. Trying to control non-natives means asserting human control over the ecosystem, this goes against the definition of wilderness. Yet, not doing so leaves traces of human effect since non-natives were primarily introduced by humans. Cole and Yung (2010) state that the emergence of wilderness values of unconfined, unfettered, unrestrained and untrammeled natural areas place more importance on freedom from human control than free from human effect. While the presence of non-natives is “unnatural”, they are a symptom of unintentional manipulation of the environment by the action of people simply visiting wilderness areas, and removing them represents us exerting control over the ecosystem. And at the same time, the presence of non-natives on campsites provides ecological services by increasing biodiversity and stabilizing erosion thereby increasing ecological integrity of the area. In the case of the BWCAW, non-natives are providing an ecological service, most are not invasive, do not spread outside of disturbed areas, and were a part of the ecosystem when the Wilderness was first established, probably because of the long history of human exploration to the lake system and campsites. Human visitation has created a novel ecosystem where common backyard weeds such as *Trifolium repens* and *Taraxacum offininale* are a part of the landscape, at least on the campsites. Whether this changes the wilderness character of the area or not is debatable. What is more obvious is the alteration of nodal areas where campsites occur. Campsites now stick out from the landscape as visitor use has, over time, created pockets of sunny, grassy areas with very few trees. This alters the aesthetics of the shorelines of the lakes in BWCAW and is a subtle but obvious “manipulation” of the ecosystem by wilderness visitors. Recreational use is a part of wilderness management, but managers should consider the long-term impacts that camping has to wilderness character in the BWCAW.

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CHAPTER 4:
APPLICATION OF AIRBORNE LIDAR IN MODELING TRAIL EROSION ALONG THE APPALACHIAN TRAIL, NEW HAMPSHIRE

Abstract

Recreation activity ultimately causes impacts to the ecosystem and soil erosion is a main indicator of trail impact. Doing comprehensive field monitoring of trail incision and widening is time-consuming and expensive. Using high resolution terrain data such as LiDAR, a type of active remote sensing technology, to measure terrain characteristics associated with trail erosion can help develop a predictive model of soil loss on the trail system. Borrowing from geomorphic and agricultural soil erosion models, this study applied a variety of terrain and hydrology characteristics at three spatial scales in relation to the trail tread. Field measurements collected soil loss as the mean vertical depth at each transect location. The model for each spatial scale and a combined model are presented. The adjusted R^2 explaining variance in soil loss is 0.57 using variables from all spatial scales. Environmental and trail design factors that were found to be significantly correlated to soil loss have implications for sustainable trail construction and management.

Keywords: soil erosion model, trail erosion, Appalachian Trail, spatial scale, LiDAR

Introduction

The Appalachian Trail (A.T.) receives an estimated two million hikers every year and offers opportunities for backcountry recreation and long-distance hiking. The A.T. accommodates heavy and spatially intensive visitation, and visitor-related impacts are largely undocumented. In the absence of professional management, such intensive visitation is causing unacceptable impacts to soils, vegetation, water, wildlife, cultural resources, and visitor experiences. The NPS Management Policies direct managers to ensure that any adverse impacts are the minimum necessary, and do not constitute impairment of park resources and values (NPS 2006). Developing sustainable recreation infrastructure, in this case a long-distance trail that can accommodate high visitation and not create adverse resource impacts, is a high priority. Identifying the factors that substantially influence soil erosion along the trail will help trail managers design, construct, and maintain more sustainable trails able to resist soil erosion, minimizing environmental degradation and enhancing visitor experiences.

Soil loss on trails

Resource degradation on trails depends on an array of use-related, environmental, and managerial factors (Leung and Marion 1996). Concentrated traffic pulverizes soil leaf litter and humus layers, which are easily lost through erosional processes. Soils then become exposed and vulnerable to wind or water erosion and compaction (Marion et al. 2016). Soil compaction decreases soil pore space and water infiltration, which in turn increases water runoff, soil erosion, and muddiness. Trails in lowland areas or with low grades are also subject to muddiness, which contributes to trail widening and additional unnecessary damage to vegetation and soils. Soil loss on trails can also substantially expand the spatial extent of recreational disturbance (Leung and Marion 1996; Marion and Wimpey, Submitted), alter natural patterns of water runoff, and cause subsequent turbidity and deposition in streams and other water bodies (Marion et al. 2016). While some degree of visitor impact is unavoidable, excessive impacts threaten natural resources and processes, visitor safety, and the quality of recreational experiences (Leung et al. 2001; Marion 2016).

Initial trail construction establishes a trail’s topographic alignments and trail width, gradient, outslope, and drainage. Numerous trail science studies have documented and described the relationship between different design factors and amount of erosion (Bratton et al. 1979; Leung and Marion 1996; Olive and Marion 2009; Marion and Wimpey Submitted). Previous studies suggest that soil erosion along trails is principally influenced by the type and amount of use, trail design and alignment features, soil type, rock content, and the density and efficacy of tread drainage features (Marion et al. 2011; Marion and Wimpey Submitted; Olive and Marion 2009). Trail grade and trail slope alignment angle are key trail design attributes that influence soil erosion (Leung and Marion 1996; Marion 2006; Marion et al. 2006; Marion and Wimpey 2007; Olive and Marion 2009). Trail slope alignment angle is calculated as the difference between the azimuth of the landform fall-line and the azimuth of the trail as it crosses the fall-line. Both variables relate to how a trail is aligned to the landform topography.

Modeling Soil Erosion

Two general approaches for modeling trail soil erosion have been applied in the literature: empirical models based on statistically significant relationships between dependent and one or more causal or influential independent variables, and physics-based models developed using equations derived from hydrology simulations and numerous inputs (Merritt et al. 2003). While no models have been specifically developed to examine soil erosion on trails, several have been adapted for modeling erosion along unpaved roads including ROADMOD, the Universal Soil Loss Equation (USLE), and the Water Erosion Prediction Project (WEPP) (Fu et al. 2010). ROADMOD allows for integration with Geographic Information Systems (GIS) to predict sediment yield from roads using empirical relationships between road surface conditions and erosion rates. Drawbacks to this model are its assumptions that there is no sediment deposition, the amount of material removed from cutslopes is insignificant, and that erosion rates are constant over space and time (Anderson and MacDonald 1998). Another commonly used empirical model is USLE, a hill-slope erosion model developed in the 1950s for use on agricultural land (Wischmeier and Smith 1978). USLE has been modified as the Revised Universal Soil Loss Equation (RUSLE) to update equation values enabling application to regions with complex topography, though it has been shown to overestimate soil erosion (Renard et al. 1991; Croke and Nethery 2006). The RUSLE model uses soil properties, slope length and grade, vegetation cover and agricultural management factors to predict annual soil loss from sheet and rill erosion in tons/acre/year. Studies and substitutions of factors have been developed for applying the equation to GIS (Tomcyzyk 2011; Mitasova et al. 1996).

GIS and LiDAR Applications to Soil Erosion Modeling

Airborne laser altimetry, also known as discrete return light detection and ranging (LiDAR) is a remote sensing technology that produces high-resolution terrain models. LiDAR data gives a point cloud of x,y,z coordinates in irregular spacing that can be filtered to view a terrain model of the earth's surface below vegetation through a variety of algorithms (Lovell et al. 2005; Zhang 2003). LiDAR data provides a much higher resolution than satellite imagery, with an increasing number of datasets providing sub-meter resolution.

Studies using LiDAR to map soils and geomorphic processes have found that using LiDAR metrics in addition to GIS environmental cover data (e.g., soil type, geology, land use, and land cover) enhances prediction models (Jebur et al. 2014; Jebur et al. 2015; Greve et al. 2012; Sankey et al. 2010). Topography is the underlying trend that defines landforms and environmental attributes such as soil particle size, soil moisture and depth to rock are related to topography. Position on the landform can determine if an area collects or disperses water and if soils are deep or shallow. Highly accurate topography data allows researchers to apply models and indices such as Curvature, Topographic Roughness, and Integrated Moisture Index. Geomorphologists, hydrologists and ecologists have found utility in spatial modeling of erosion through these GIS indices (Romkens et al. 2002; Yilmaz 2009).

Through the advent of GIS and remote sensing technologies, accurate predictions of environmental phenomenon across a broad area at multiple spatial scales can be performed. This scaling up of prediction is possible by using metrics from remotely-sensed data and by using surrogates of data collected in the field in the GIS environment. Topographic metrics from LiDAR have been used in a variety of geomorphic applications, including predicting landslides, erosion potential after a wildfire, and forest road-induced erosion (Jebur et al. 2014; Sankey et al. 2010; Tarolli et al. 2013). Some typical variables used in describing geomorphic phenomena include calculating slope, aspect, curvature, and topographic roughness and wetness. Aspect relates to potential solar radiation. Curvature identifies concave versus convex landforms and can segregate based on planform curvature or profile curvature. Planform curvature is perpendicular to the slope and relates to the convergence and divergence of flow across the surface. Profile curvature is parallel to the slope and relates to the acceleration and deceleration of flow across the slope as it indicates the direction of maximum slope. It is important to know where along the trail water is collecting or shedding. Topographic roughness is a measure of land surface variability. Topographic Wetness Index (TWI) quantifies topographic control on hydrological processes, specifically to reveal the influence of topography on the location and magnitude of saturated regions of runoff generation (Jebur et al. 2014).

GIS has also been used in determining watershed metrics. GIS software allows one to calculate watershed delineations based on detailed digital elevation models. Software tools can also delineate streams and compute *flow length*, the distance from the top of the watershed to the outpour point over the topography, and *watershed head*, the difference in elevation from the top of the watershed to the outpour point.

Using GIS to Model Trail Erosion

Few studies have examined GIS applications to model trail erosion. Previously, digital elevation data (10m and 30m) has been too course to accurately describe erosion processes along trails, which have an average width of 0.5m. Cakir (2005) modeled trail erosion with 3m, 5m 10m, and 30m elevation data. She found significant relationships between trail slope alignment angle, landform curvature, interaction of grade and trail slope alignment angle, and the grade of the trail at various resolutions, with 5m being the most significant.

Tomcyzk (2011) looked at the susceptibility of plants to trampling and the vulnerability of soils to erosion processes to identify the most resilient areas where trails should be located. The researcher adapted the USLE equation to GIS and trail system analyses using soil map and topography data. Land cover maps were also used to classify vegetation and provide a C factor from the USLE equation based on vegetation type. The overall product gave a resiliency rating for the entire protected area. Tomcyzk and Ewertowsksi (2013) used regression tree analysis to create a predictive model for trail condition, using trail width as their dependent variable. They used similar GIS-derived indices to the ones presented in this study including curvature, aspect, and landform slope. They found plant communities, elevation, aspect and slope to be important variables. They did not include precipitation in their model.

In addition to topographic data, spatial vegetation data can also be used to model trail condition. A study in Tasmania modeled trail condition in terms of stability or potential for degradation using a number of GIS data layers (Hawes et al. 2013). They derived trail and landform slope, calculated waterflow as the upslope catchment area above the trail segment, and substituted a “bogginess” factor with a vegetation map identifying obligate wetland species. They also modeled vegetation with woody roots in the substrate by selecting areas along the trail that had a certain vegetation type. Their methods produced 50% accuracy in predicting the trail condition class, with another 38% accuracy within one condition class from the observed.

Researchers have attempted to model the optimal trail location by using GIS data to pinpoint terrain that is the least susceptible to erosion (Tomcyzk and Ewertowski 2013).

Researchers applied GIS layers from a 5m DEM to the USLE and PWER soil erosion models, along with other land cover factors to determine environmental sensitivity. They did not include trail design factors such as trail slope and trail slope alignment angle. The models allowed environmental resilience comparisons for alternative potential trail alignments to help trail managers select the most sustainable locations.

The use of GIS in analysis of trail characteristics allows researchers to look at multiple spatial scales that may be hard to detect in the field. For example, watershed metrics are hard to capture in the field because the area is so large but with a high resolution DEM, these metrics can easily and accurately be calculated. Detection of landscape pattern is sensitive to spatial scale, to both the spatial resolution and the total area or extent of a spatial dataset (Turner et al. 1989). Erosion processes are conditioned by type of soil, porosity, slope, and rock fragments and these factors can have different relationships to stabilizing sediment at different spatial scales (Poeson et al. 1994). There is an interaction between the hierarchies of spatial scales with small, low-level systems being a part of a sequence of large, high-level systems (DeBoer 1992). When looking at sediment yield from watershed, researchers found that watershed area was an important predictor of sediment yield (Lane et al. 1997). Thus, when modeling geomorphic processes, one should be sensitive to spatial scale.

There is a need for additional research to further develop trail erosion models to determine where and why trail degradation occurs, and the relative influence of causal and non-causal factors. Such models could be powerful tools to land managers in designing sustainable trail networks and identifying portions of existing trails most in need of re-alignment or maintenance.

This exploratory research seeks to advance the state-of-knowledge and capabilities offered by trail erosion modeling by applying a comprehensive array of field measurements combined with the exploration of GIS and LIDAR technologies to create an additional suite of variables at multiple spatial scales and extents. This more comprehensive suite of independent variables will be employed in geospatial modeling to investigate relationships between topography, watershed attributes, trail design elements, substrate characteristics, and trail soil loss. Specific objectives include:

1. Characterize the severity of erosion along sections of the A.T.
2. Create hydrologic and topographic indices using LiDAR-derived digital terrain models.

3. Generate trail and watershed characteristics at multiple spatial scales and extents in GIS using LiDAR-derived digital terrain models.
4. Statistically analyze the influence of field and GIS-generated variables and indices in explaining trail soil erosion.
5. Develop a prediction function for soil loss on trails.

We expect that GIS analyses with LiDAR data combined with on-the-ground measurements where there is no GIS surrogate should provide predictive equations determining conditions that relate to high levels of soil loss. Trail managers can use this information to identify environmental or trail design factors that lead to the trail being highly eroded. This research is a subcomponent of a much larger study collecting similar data on trail conditions for the entire A.T. over a three-year period. Knowledge from this exploratory research is intended to guide similar GIS modeling for the entire A.T. Due to the substantial dataset size and heterogeneity we expect that research to provide more universal knowledge about factors affecting soil loss and predictive models for the A.T. and other similar trails.

Study Area and Methods

Study Area

The 2,175-mile A.T. was completed in 1937 and is the nation's oldest and most well-known National Scenic Trail. The A.T. trail receives intensive visitor use from an estimated two million hikers a year. The A.T. trail corridor is a nationally significant NPS greenway park that protects 280,000 acres and connects some of the largest remaining tracts of undeveloped wildlands in the Appalachian Mountains. The section of trail measured in this study is 15km across a 53km stretch of the Appalachian Trail located in the White Mountains, outside of Lincoln, NH (Figure 4.1). In this section, the trail crosses two ecoregions: a Red Spruce (*Picea rubens*) and Balsam Fir (*Abies balsamea*) forest, and a Sugar Maple (*Acer saccharum*), Birch (*Betula spp*) and Beech (*Fagus grandifolia*) forest. The terrain varies from steep mountains to gentle valleys with elevation ranging from 440m to 1200m along the trail. Precipitation varies with elevation, from 40-85cm of precipitation a year (PRISM 2010).

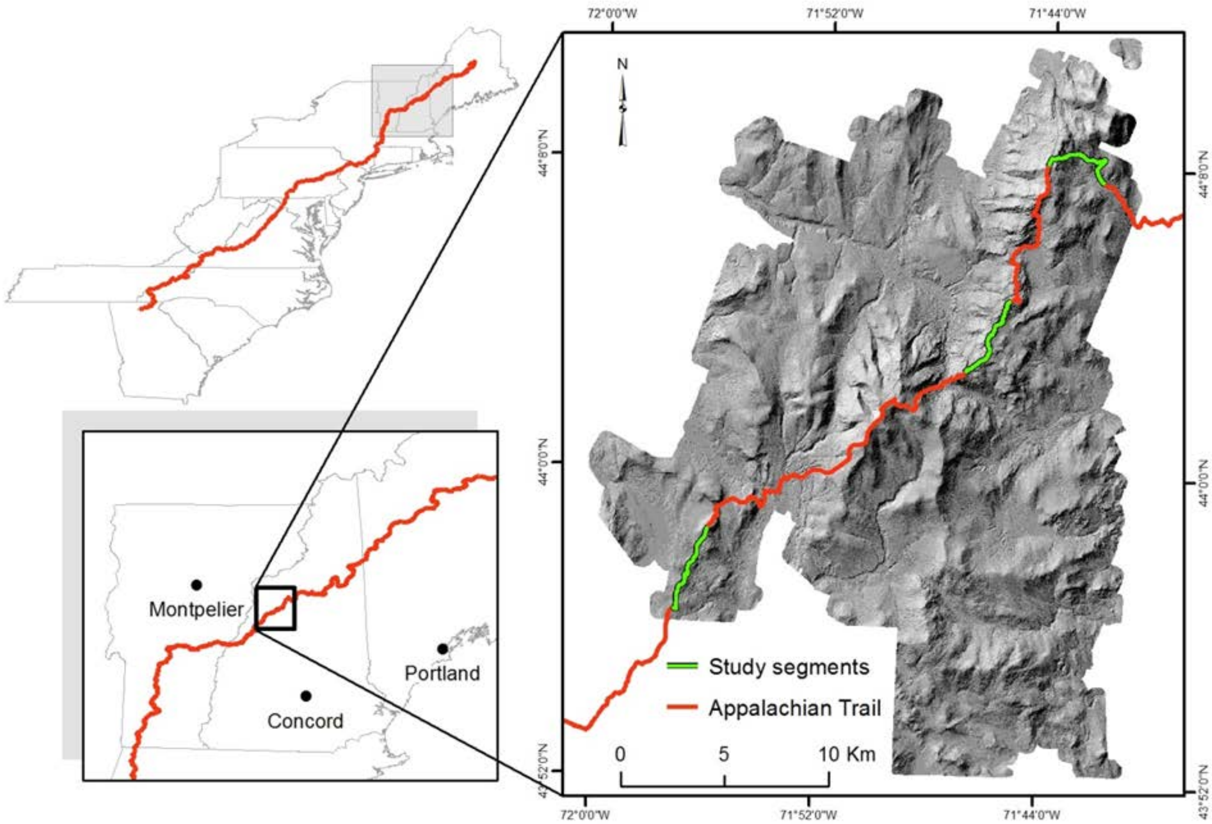

Figure 4.1. Study Area. The green sections show 5km segments that were measured along the A.T. in NH. The hill-shade map is the footprint of LiDAR available for the project.

Sampling

Trail characteristics were measured in the field and through GIS using LiDAR data. A model of soil loss was developed using variables from field measurements and GIS-derived measures and indices across a variety of spatial scales and extents. Fieldwork to measure soil loss and an array of trail properties was conducted in June 2015 by eight field staff. Measurements were taken at 135 sample locations, broken up into three 5km segments of trail along the Appalachian Trail in the White Mountains National Forest where LiDAR was flown. Error from spatial autocorrelation was reduced by using a Generalized Random Tesselation Stratified (GRTS) approach to select both the 5k segment locations and the 45 transect points along each segment from the 53km of trail with LiDAR data. According to the theory of spatial autocorrelation, sample locations that are farther from one another provide a more independent sample about the target area than sample points clustered close together (Stevens and Olsen 2004). GRTS forces the sample to be spatially representative and creates a random sample where every sample point has a probability of being selected. GRTS selects sample points that are spatially distributed across the study area (Stevens and Olsen 2004). The GRTS sampling selection was done using the developed program in the R software package (Kincaid and Olsen 2011).

The three segments provide a diversity of topography, substrate and vegetation. Increased diversity in conditions could create a more robust model of trail erosion that is not so site-specific. The northern-most segment is in the sub-alpine zone characterized by Balsam fir and very thin soils, a few of the transects have become stabilized as they have eroded down to bedrock. The landscape in this segment is hummocked with large boulders and glacial till. The middle segment traverses terrain between the valley and the sub-alpine zone. There was more evidence of trail maintenance here than any other section, with rock steps going up steep fall-line trails. This section contains large glacial erratics (>3m) covering the landscape and trail with very thin soils on top (3-5cm). Deep pockets of soil lie between the boulders, and the trail in these sections is deeply eroded.

The southern-most segment is located in a valley. Due to the ecosystem type, much of the organic litter is broadleaf leaves from maple, birch and beech trees. This area is in a dynamic equilibrium that prevents large erosion from occurring. The leaves act as a blanket on the surface of the soil and protect the trail tread from erosion. Hikers never fully pulverize the leaves to get to the mineral soil because this areas doesn't receive much use. Between the aggregation of organic litter and the low foot traffic the area receives, the trail system is quite stable and the CSA erosion values at the transects are low compared to other areas. The leaves also protect the trail from erosion by rainfall, the leaves intercept the rain drop and much of the kinetic energy and erosive potential of the raindrop is removed by the presence of the leaves versus exposed mineral soil. The leaves also create a complex micro-topography for water running down the trail, which slows water down and increases infiltration, reducing erosion potential.

Field Data Collection

In the field, the point sampling layer was uploaded onto Garmin64 handheld GPS units, allowing researchers to navigate to each sample point using the GPS, where temporary transects perpendicular to the trail tread were established to measure indicators. A Trimble XH, 6000 series GPS with floodlight technology and a GNSS satellite sensor was used to record an average of 50 points at each transect for more accurate location measurements. The 50 points were averaged on the GPS, then differentially corrected to give the final x,y coordinates. The trail centerline was also captured using the Trimble by walking the center of each trail segment. Given this collection method, there is more confidence in the location of the transect points than of the line. Thus, in editing of the GPS data, the lines were adjusted when necessary to go through the point data collected. Of the point data, 48% if the data points had horizontal accuracy within 1m post-processed and 86% of the data points were within 2m post-processed. Any data points with greater than 2m horizontal accuracy were omitted from the study. A map of transect locations and the A.T. centerline were created from the GPS data.

At each sample point, a transect was established perpendicular to the trail tread to span the width of the trail. Along the transect, soil loss was measured in cm^2 by measuring the cross sectional area (CSA) of the trail tread. The CSA transect is established by placing temporary stakes on either side of the trail and stretching a taught line across it. Depth measurements from the line to the tread surface were measured at fixed intervals of 10 cm (Cole 1983). The CSA method was amended slightly for this study to capture historic erosion as well as erosion from current use. Previous studies placed the ends of the transect on either side of the trail where 95% of foot traffic occurs (Marion et al. 2006; Olive and Marion 2009). In this study, the transect ends were expanded to where the trail was determined to have been originally constructed. Figure 4.2 shows an example of where the transect is placed (dashed line) compared to the current tread. This method was employed to capture total soil loss that has occurred since the trail was first constructed; trails in the study are estimated to be over 60 years old.

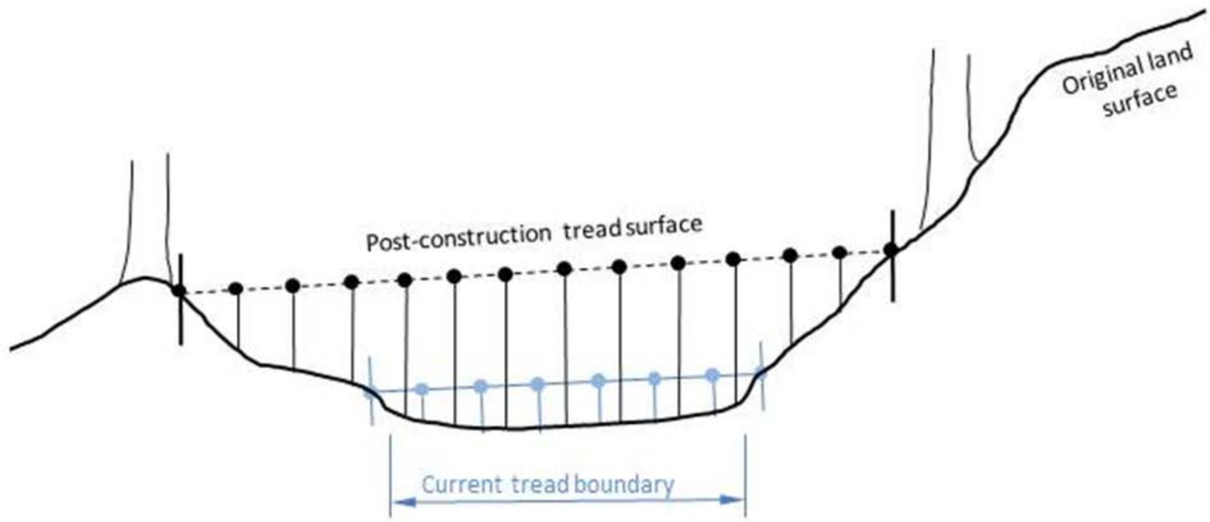

Figure 4.2. Measuring historic soil loss. The historic trail erosion was measured at the dashed line indicated the estimated post-construction surface of the trail as opposed to the current tread that is being actively walked on now.

At the trail transect, CSA was measured along with other characteristics including: soil texture, tread composition, grade, and trail slope alignment angle. Tread composition is the relative percentages of vegetation, organic litter cover, exposed soil, exposed roots, rock, gravel and water that occur across the transect line (Marion and Hockett 2008, Marion and Leung 2001, Olive and Marion 2006). Trail grade was measured with a clinometer with one field staff walking 3m in an uphill direction from the transect point and sighting the grade. Trail slope alignment angle is the difference between the bearing of the trail and the bearing of the landform, bearings were measured at the transect.

At each transect point the "trail corridor watershed" was assessed; it is defined as the artificial catchment area starting from the transect and proceeding uphill along the trail to a boundary where water is diverted into two directions either via a slope change or 100% effective tread drainage feature such as a water bar (Figure 4.3). Small drainage features diverting lesser amounts of water from the trail and water in-pour points were also mapped with the Trimble. Within the trail corridor watershed the following attributes were assessed and averaged: trail slope, trail slope alignment angle, tread width, ground cover, substrate, and canopy cover. Ground cover type assessed for the trail corridor watershed included the categories: soil, organic soil, rock <5cm, rock 6-30cm, rock >30cm, bedrock, exposed roots, vegetation, human-placed wood, or litter. Substrate type was estimated by examining the backslope cut of the trail and surrounding surface features.

The "upslope landform watershed" is defined as the traditional watershed created from the terrain in an uphill direction from the trail transect, including all surface area that might contribute water to the trail transect. At the upslope landform watershed, the ratio percentage of ground cover type, substrate type, shrub cover, canopy cover, estimated slope and watershed length were recorded in the field. All measurements taken in the field were recorded on an iPad using Qualtrics© offline forms.

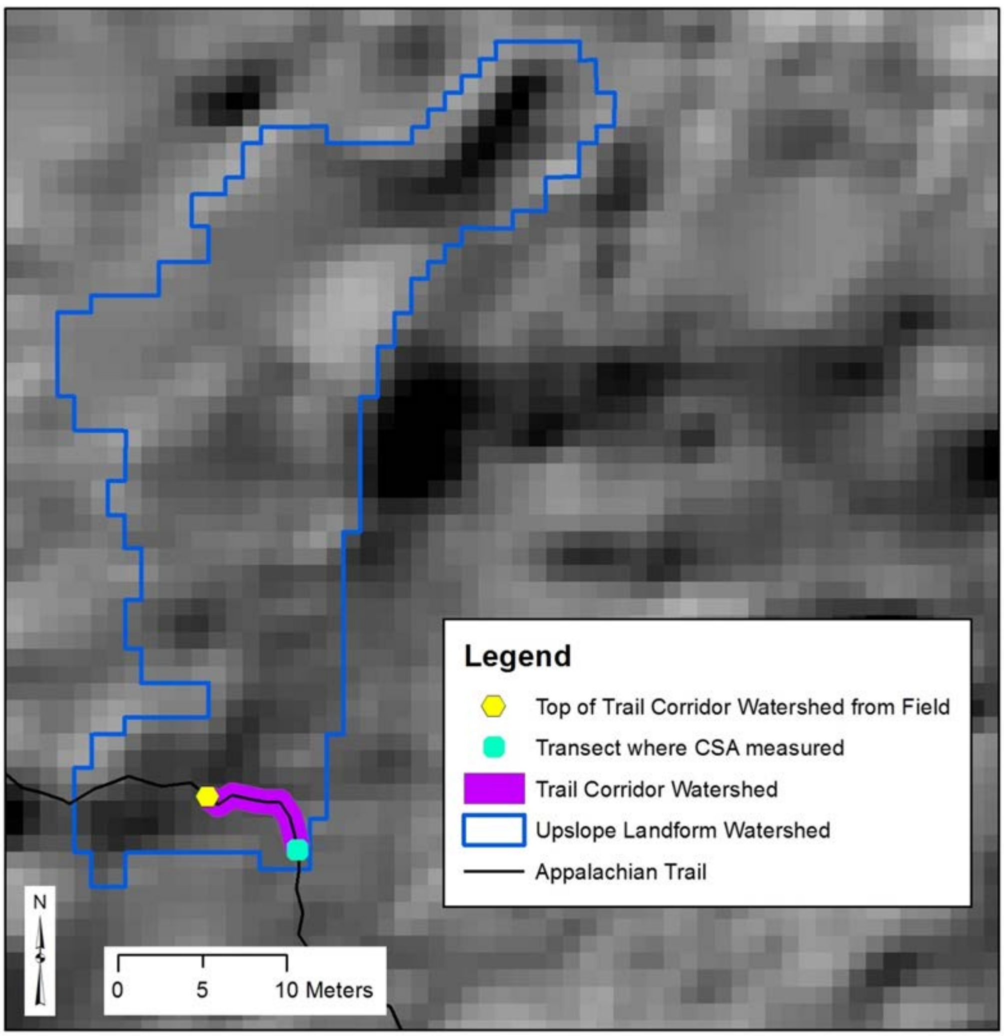

Figure 4.3. Three spatial scales of measurement for variables related to trail soil loss. The cyan point marks the "transect location" (1st spatial scale) and the purple polygon delineates

the “trail corridor watershed” (2) with the upper boundary marked in yellow. The polygon outlined in blue depicts the “upslope landform watershed” (3) delineating the contributing area above the purple polygon, delineated with GIS.

GIS Analysis

Point cloud LiDAR data are available through the U.S. Geological Society (USGS) for a 484 square km swath of the White Mountains in New Hampshire. LiDAR was flown at 1m nominal point spacing with vertical accuracy of 13cm RMSE by Photo Science, a USGS contractor, during leaf-off season in November 2011 when there was no snow on the ground. Point cloud data were used to create a 1m bare earth digital elevation model using Optech, GeoCue, Terra Scan and Terra Modeler software for automated classification and manual inspection.

Each of the terrain characteristics, including trail grade and trail slope alignment angle, were also computed in ArcMap 10.3 GIS software using the 1m Bare Earth DEM for each of the three spatial scales shown in Figure 4.3. Trail grade was measured in GIS by placing a point 5m in the uphill direction from the transect and calculating slope between the points. This was done to mimic the process in the field. Trail slope alignment angle was measured several ways for the trail corridor watershed to account for the winding nature of the trail system and determine if the trail is contour- or fall-line-aligned. The bearing of the trail is calculated by taking the bearing between two points, one where the erosion transect was collected, and one where the edge of the trail watershed boundary is defined. The distance between the two points varies with each transect. TSA was measured by segmenting the trail into 5m chunks and averaging TSA over these segments, and by calculating the overall bearing from the start of the trail corridor to the end.

Additional variables were derived using GIS techniques, including slope, aspect, curvature, flow accumulation, topographic wetness index, topographic roughness, and watershed length and head. Slope, aspect, curvature and flow accumulation were measured using the Spatial Analyst extension in ArcMap 10.3. The Slope tool in ArcMap calculates slope for each pixel by looking at 3x3 window and calculating the change in elevation from left to right and from top to bottom around the center pixel (Horn 1981). Slope was also calculated using the output drop raster in the flow direction tool in ArcMap, where slope is calculated by taking the maximum slope from a center pixel to each of its 8 neighbors in a 3x3 window (Travis et al.

1975). The Curvature tool in ArcGIS calculates the second derivative of a surface within the 3x3 moving cell window. Overall curvature, profile and planform curvature were calculated.

Topographic wetness index (TWI) is shown in the equation below where A_s is the specific catchment area (m^2m^{-1}) and β (radian) is the slope gradient in degrees.

$$TWI = \ln(A_s/\tan\beta)$$

Topographic roughness was measured by running standard deviation of the elevation. To calculate the standard deviation of elevation within a cell window, the ArcMap Focal Statistics tool was applied to varying window sizes, for example 3x3, 5x5 and 7x7 windows were run. The larger the window, the more generalized the product, as there is more data to average.

For the "upslope landform watershed", watershed metrics such as flow length and head were calculated in GIS. Flow length is the length of the longest flow path within a given basin. It was calculated using the Flow Length tool in ArcMap in the downslope direction to determine the distance along the flow path from each cell to an outlet. With this, the flow length from the transect point to the top of the upslope landform watershed was calculated. The head, or difference in elevation between the top of the watershed and the transect point, was also calculated off of the Bare Earth DEM.

For GIS-derived variables at the transect spatial scale, raster values were extracted from the cells containing the transect point locations. For the trail corridor watershed spatial scale, the zonal statistics tools (both mean and mode) were used for raster data. Trail slope at this spatial scale was calculated in two ways. First, by taking the rise/run from the elevation of the transect and the elevation of the upper trail corridor watershed boundary. Second, splitting the trail centerline into 5m sections along the length of the trail corridor watershed, calculating the slope of each section, and averaging these values. The upslope landform watershed (the blue polygon in Figure 3) was delineated using the Watershed tool in ArcMap with the associated trail corridor (purple polygon in Figure 3) as the pour "point". The Upslope landform watershed GIS variables were calculated by running zonal statistics (both mean and mode) of slope, topographic roughness, TWI and aspect rasters.

Modeling

Soil erosion measured on trails includes erosion from water and wind erosion, soil displacement by traffic, and soil compaction. The dependent variable employed in these trail erosion regression models is mean trail depth, calculated by averaging the vertical CSA measures for each transect. This indicator factors out differences in tread width, which can inflate or deflate total erosion measured across the trail. Predictors of the model include both variables measured in the field and in the GIS environment. A randomized portion of the data, 70%, was used to construct or train the model. In some cases, we performed multiple methods of measuring the same variable. For example, slope was measured in the field, and it was measured in GIS using two different algorithms at 3 spatial scales. To reduce instances of covariance, forward and backward stepwise regression using minimum Akaike information criterion (AIC) was performed on variables of the same category modeled with the dependent variable. The most significant variable was selected from each category and these variables were input into the final model.

Next we applied four final models relating to different spatial scales: 1) transect scale (cyan dot in Figure 4.3), 2) trail corridor (purple polygon in Figure 4.3), 3) upslope landform watershed (blue polygon in Figure 4.3), and 4) an integrated model combining variables from all spatial scales. Ordinary Least Squares multiple linear regression was run on the final set of variables, and variables were further selected through forward and backward stepwise techniques using R software. Five outliers were removed using Cook's Distance threshold and the variance inflation factor and a correlations matrix were examined for each variable to detect unacceptable levels of multicollinearity. The model was then validated with the 30% of the field data withheld from the training set using simple linear regression. The validation dataset had a balanced distribution of data points from each of the three segments.

Table 4.1. List of variables used to predict soil loss at trail transect. Variable categories in bold were reduced to one significant variable for each spatial scale to be put in model.

	Spatial Scale		
Variable Category	**Transect**	**Trail Corridor Watershed**	**Upslope Landform Watershed**
Slope	Grade* Slope Ratio (trail slope/landform slope)* Slope (from Horn algorithm)† Slope (from Travis et al. algorithm)† Slope ratio (trail slope/landform slope (Horn)† Slope ratio (trail slope/landform slope (Travis)†	Avg. Grade * Trail watershed grade (from elevation at start/end)† Trail watershed grade (Avg. of slope of line between start/end points split in 5m seg.)† Trail watershed grade (mode of slope of line between start/end points split in 5m seg.)† Slope ratio (mean trail watershed slope/landform slope (Horn)† Slope ratio (mean trail watershed slope/landform slope (Travis))† Slope ratio (mean trail watershed slope segmented /landform slope (Horn)† Slope ratio (trail watershed slope segmented/landform slope (Travis))† Slope ratio (mode trail watershed slope segmented/landform slope (Horn)† Slope ratio (mode trail watershed slope segmented/landform (Travis)†	Grade* Mean Slope (Horn)† Mode Slope (Horn)† Mean Slope (Travis)† Mode Slope (Travis)†
Trail Slope Alignment Angle (TSA)	TSA* TSA (trail bearing-landform aspect)†	Avg. Trail Slope Alignment * TSA (mean trail azimuth from start to end of watershed, aspect of landform)† TSA (mean trail azimuth from 5m seg., aspect of landform)† TSA (mode trail azimuth from 5m seg., aspect of landform)†	
Size		Length trail watershed* Trail Watershed size (in m^2)†	Length*
Precipitation	Precipitation (PRISM model)†	Precipitation (PRISM model)†	Precipitation (PRISM model)†
Soil Texture	Soil Texture *		
Ground Cover	Trail Tread Characteristics (ex. % of bare soil, litter, vegetation)*	Avg. Ground Cover (ex. % soil, vegetation, litter, rock)*	Avg. Ground Cover*
Substrate Type		Avg. Substrate Type (ex. % of soil, rock by size class, bedrock)*	Avg. Substrate Type*
Curvature	Curvature at 1, 10 and 30m‡ Planform Curvature at 1, 10 and 30m‡	Mean & mode values of: Curvature at 1, 10 and 30m‡ Planform Curvature at 1, 10 and 30m‡	Mean & mode values of: Curvature at 1, 10 and 30m‡ Planform Curvature at 1, 10 and 30m‡
Aspect	Landform aspect *	Mean & mode values of: Aspect†	Mean & mode values of: Aspect†
Topographic Roughness	Standard deviation of elevation for 3x3, 5x5 and 7x7 window‡	Mean & mode values of: Standard deviation of elevation for 3x3, 5x5 and 7x7 window‡	Mean & mode values of: Standard deviation of elevation for 3x3, 5x5 and 7x7 window‡

Watershed metrics	Flow Accumulation‡ Topographic Wetness Index‡	Sum Flow Accumulation‡ Mean and mode values of: Topographic Wetness Index‡	Sum Flow Accumulation‡ Watershed head Watershed flow length Mean and mode values of: Topographic Wetness Index‡

* Field-collected data
† GIS surrogate for field data
‡ Novel GIS-derived data

Results

Regression Results

Results from the regression analysis are shown in Table 4.2 where the adjusted coefficients of multiple determination (R^2) represent the proportion of explained variation in soil loss, measured by mean vertical depth at each transect, by the included independent variables. Regression models where applied to the three different spatial scales, at the transect, the trail corridor and the upslope landform watershed. A final model was developed that combined significant elements from all spatial scales (Table 4.2). The combined model explains 57% of the variation in soil loss, measured as the mean vertical depth at each transect. There were significant variables for each of the spatial scale models. The upslope landform watershed model explained the least variation in soil loss, at 39%. An additional 4% of the variance was explained with the transect scale model, with another 5% of variance explained by the trail corridor model. The combined spatial scale model performed the best, and its inclusion of variables from each of the spatial scales indicates that the interaction of topography, substrate and trail design from the transect to the watershed scale all help explain trail soil loss.

Analysis of Spatial Scales

The analysis of trail soil loss was divided into different spatial scales to identify mechanisms that influence where water is traveling downhill across the landform and along the trail. Both spatial scales could explain soil loss at the particular location of the transects measured. At the transect scale, precipitation, trail grade and TWI are variables in the model with precipitation and trail grade being significant at the 0.05 threshold. Landform slope measured with the Travis et al. (1975) algorithm, which measures the steepest path in a 3x3 window, is the only variable to make it into the “combined spatial scales” model. For the trail corridor model, all of the variables were incorporated into the “combined spatial scales” model. Precipitation and mean grade of the trail corridor were the most significant at $p<0.001$. At the “Upslope Landform Watershed” scale, precipitation, watershed head and landform slope predict soil loss, with precipitation being the only significant variable. Landform slope of the watershed was also incorporated into the “combined spatial scales” model.

Table 4.2. Regression results of modeling trail soil loss (mean trail depth) at three spatial scales. Sample size of each model is 79.

Variables	**Regression models**			
	Transect Scale	**Trail Corridor Scale**	**Upslope Landform Watershed Scale**	**Combined Spatial Scales**
Precipitation	2.6[a] (<.001)[b]	2.9 (<.001)	3.4 (<.001)	2.8 (<.001)
Trail grade at Transect (field)	2.0 (.044)			
Landform Slope at Transect (Travis)	0.8 (.129)			1.6 (.004)
TWI at Transect point	1.1 (.137)			
Trail Corridor Mean Grade (field)		3.9 (<.001)		3.6 (.003)
Trail Corridor Slope ratio (split/GIS Landform Slope (Horn))				17.9 (.146)
Trail Corridor Mean Substrate Type: Percent Soil		-0.3 (0.13)		-0.4 (0.048)
Mean Landform Slope along Trail Corridor (Horn)		-1.2 (.015)		-1.2 (.018)
Upslope Watershed Head			0.9 (.079)	
Upslope Watershed Flow Length				0.3 (.005)
Mean Landform Slope for Upslope Watershed (Travis)			-0.53 (0.091)	-.8 (.001)
Constant	-73.5	-43.9	-50.1	-34.6
Adjusted R^2	**0.43**	**0.48**	**0.39**	**0.57**
F-stat	16.51	20.02	18.88	14.96
Residual Standard error	64.13	61.25	66.08	55.36

[a] Coefficients of mean vertical depth of soil loss (cm)
[b] Two-tailed t-test significance

Precipitation is significant at every spatial scale, indicating that soil loss on trails is driven by amount of water. Erosion likely occurs during and following substantial rain events where runoff causes sheet or rill erosion of trail tread soil. A goal of sustainable trail design and construction is to create side-hill treads that are “hydrologically invisible” – where water flows across “out-sloped” treads without being transported any substantial distance along their length. However, most unsurfaced trails are susceptible to soil compaction and displacement during initial use that inevitably cups their treads so that water is intercepted and transported down their treads. Water is intercepted and accumulates on a trail from adjacent upslope areas and from direct rainfall on the tread watershed, the “footprint” of the trail itself. When water is channelized within an incised tread its velocity increases, yielding greater erosive force. Water is only diverted when: 1) the trail is sufficiently out-sloped that water moves across and off the lower edge of the tread, 2) a natural dip, grade reversal, exposed roots, or rocks divert water off the tread, or 3) a human-constructed tread drainage feature (e.g., water bar, drainage dip, or tread grade reversal) divers water off the tread.

In the model that combines variables from all spatial scales, it becomes clear that topography, substrate and precipitation all influence soil loss along trails. The more precipitation received, the more soil loss occurs. Upslope watershed flow length was not an influential variable in the upslope landform watershed scale model, but it was for the "combined spatial scale" model. Depending on infiltration rates, longer flow lengths allow more water to accumulate and run downhill, delivering more water to a trail. Slope has different effects on soil loss at different spatial scales. Steeper trail grades correlate to higher levels of soil loss, which is expected and incorporated into most soil erosion models. Greater slopes at the micro-topography level, where landform slope was measured at the transects, also equate to higher soil loss. However, landform slope of the trail corridor and upslope watershed both have a negative relationship with soil loss at the transect.

Higher landform grade of the upslope watershed may indicate that water more easily moves across and off the trail, with less likelihood that it is diverted along a trail, causing erosion. The trail corridor slope and the slope of the landform directly at the transect point indicate that micro-topography surrounding where soil loss was measured along the trail, and the slope of the trail corridor, where most of the water crossing the trail transect point is likely to be coming from, are influential factors for soil loss. Given the 1m resolution of the DEM and average tread width of 0.75m, the mean slope of the landform within the trail corridor could be measuring the degree of out-sloping occurring along the trail. In this case, less mean trail corridor landform slope is equivalent to less out-sloping, which correlates to greater soil loss. Results could be confounded by the resolution of the DEM, which is at 1m. In the hillshade of the area, the trail can be seen in some cases, but not all, the resolution of LiDAR is not fine enough to always be able to pick out the slope break of where a trail is occurring along the landscape, using 0.5m data or finer may add more insights.

In the variable importance plot (Figure 4.4), precipitation, trail corridor mean grade and substrate of the trail corridor are the most influential factors. Precipitation determines how much water falls onto the trail and surrounding areas that may generate runoff onto the trail. Assuming that most of the measured trail soil loss is from water erosion, the finding that precipitation is a significant variable in each of the models would be expected. Environmental characteristics such as precipitation and substrate are shown to be very influential on the amount of soil loss (Fu et al. 2010). The substrate of the trail corridor was recorded as either soil, rock at 4 size classes including bedrock, roots or human-placed wood. Soil was the only substrate type that the regression modelling determined to be significant. In the models, less soil substrate correlates to more soil loss. We would expect that if the trail was predominantly rock, that most of the soil had already eroded. If the substrate is predominantly soil and it hasn't eroded, then it could indicate that areas with high soil cover are relatively stable areas that do not very erosive.

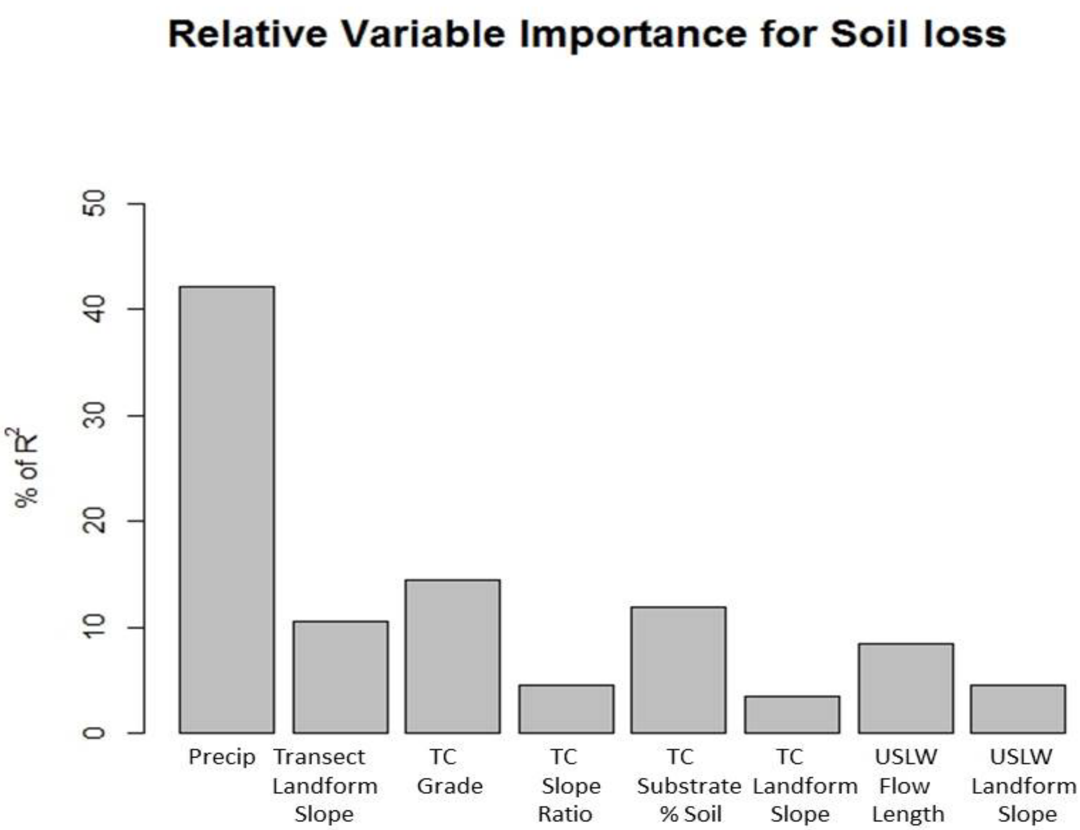

Figure 4.4. The variable importance plot for the final "Combined Spatial Scales" model (Adjusted R^2 = 0.57). Metrics are standardized with a sum of 100%.

Trail grade is an influential attribute of sustainably designed trails. A trail corridor's mean grade and slope ratio are included in the "combined spatial scales" model. Higher gradients equate to higher levels of soil loss, which is consistent with soil erosion modeling in other fields. Steeper slopes have more potential energy and water travels down them at faster rates, scouring and transporting soil along the way. Higher slope ratios for the trail versus the landform also correlate to higher levels of soil loss. In trail construction, a sustainability rule is to keep the grade of the trail at or below half of the grade of the prevailing landform. Higher slope ratios indicate trails that are more closely aligned with the fall-line of the landform, the shortest route that water would flow down a hill. Trails that have slopes that more closely match the grade of the landform are more likely to erode quickly.

Model Validation

A spatially balanced sample of transects from the three A.T. segments was used to validate the regression modeling results. The variables and corresponding coefficients identified through regression modeling for each spatial scale was applied to test data of 37 transects not included when constructing the models. This was done to eliminate the effect of spatial autocorrelation. Given the small sample size for the validation results, higher variance in model accuracy is expected. All four of the models performed with R^2 above 0.43. When comparing numbers that the model predicted versus what was observed in the field, the transect scale model performed the best, with an R^2 of 0.61. While the combined spatial scale model had explained the highest percent of soil loss variance, the validation yielded a predicted vs. observed value correlation of 43%. The relatively small sample size, and a single run of the values used as observations may explain the discrepancy between the predicted model performance and the observed. Regardless, the correlations between the model parameter output and the observed data reveal that these models are valid tools in predicting soil erosion along the trail.

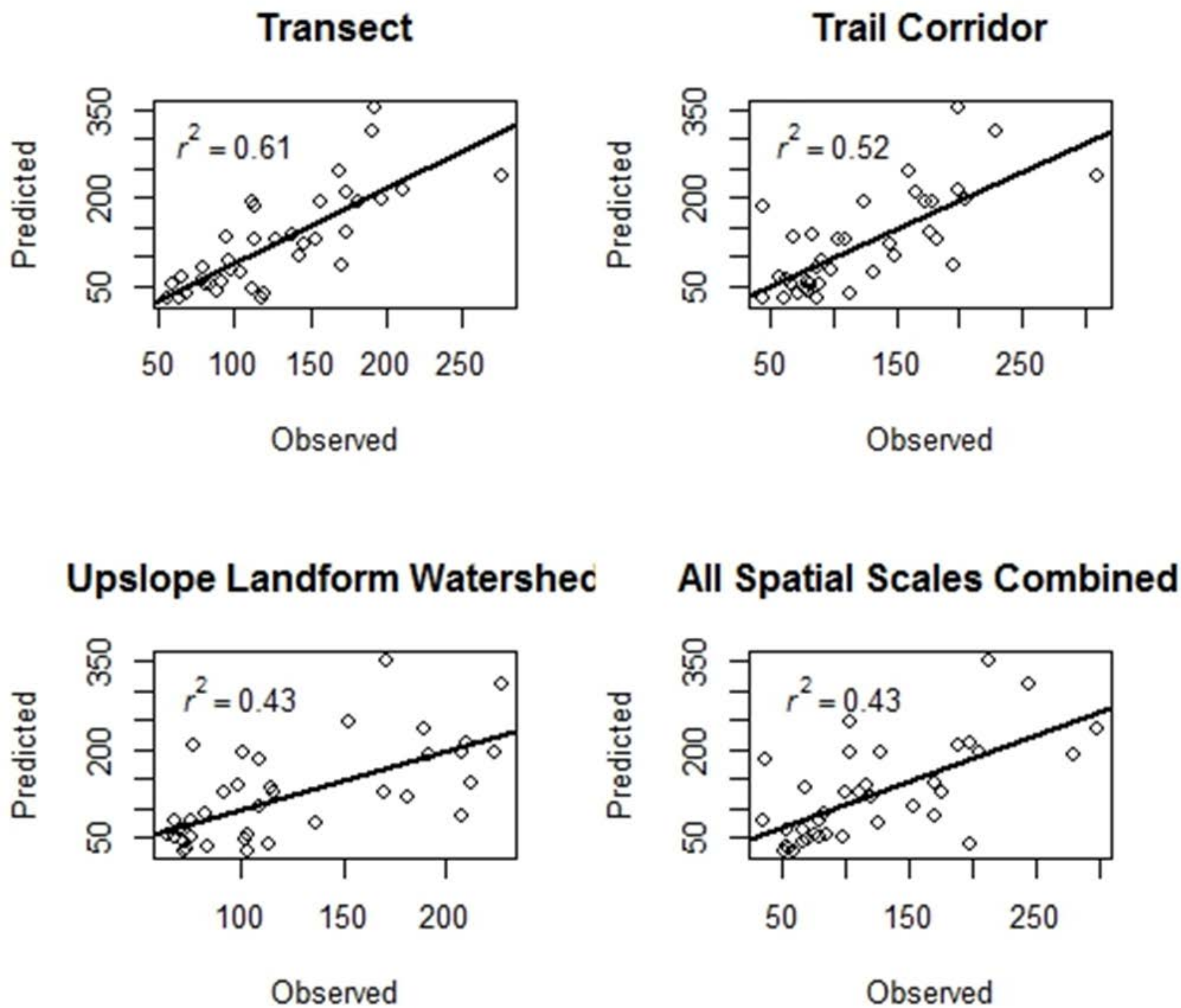

Figure 4.5. Performance of competing models on the 30% testing subset of mean vertical depth data (N=37).

Discussion

Improvement of regression equations

The best model presented in Olive and Marion (2009) to explain soil loss, measured by CSA of the trail tread, had an R^2 value of 0.32. They included soil texture variables, use level, use type, TSA, trail grade and topographic position. Fall-line aligned trails and steeper slopes were significantly correlated to soil loss. Through the application of GIS and LiDAR data this study added several new terrain and watershed variables. While this study used a different dependent variable to control for trail width variability, soil loss on trails is better explained with the model presented in this paper, possibly because it included terrain characteristics from the three spatial extents, and precipitation. Broadening the spatial extent of analysis provided several new variables that relate to the soil erosion process on a watershed scale, which proved to be significantly related to trail soil loss.

Tomcyzk (2011) also employed GIS analyses, finding higher incidences of trail incision when their model predicted the landscape was very susceptible to erosion. However, there are no multivariate statistics performed in their paper, and although they included several soil erosion models such as USLE, they did not include precipitation or trail-specific variables. A logical progression for the modeling performed in this research is to more thoroughly develop the model using larger datasets from all A.T. areas with LiDAR data. It is likely that predictive models may vary by region, but once developed they could be applied to non-sampled areas. One limitation to doing that, is that some of the variables included in the final model were collected in the field, so one would still need to get a representative sample of the trail or trail segment being modeled.

GIS Surrogate data

Since not much work has been done using GIS surrogate data in the measurement of trail characteristics related to soil loss, this study incorporated both measurements in the field and surrogate GIS data in the modeling. Resolution of the digital elevation model used will have implications on how accurate the data is compared to what is measured in the field. With 1m data, slopes over an area larger than 3m would probably be quite accurate, but with smaller areas the resolution of the DEM becomes a limiting factor. Some trail corridors were less than a few meters in length, but most were larger. In the initial categorical regression models, slopes that were measured in the field, both at the transect and for the trail corridor, were more strongly correlated than slopes measured with GIS. Slope of the landform, and of the watershed had higher correlation when using the GIS-derived layer. This is largely a function of scale. At the transect level, 1m resolution data is not fine-grained enough to mirror measurements in the field. GIS products were of more use at the larger spatial scales of the watershed level and when not directly tied to the linear trail. GIS measurement error occurs from relating point and line features to the grid design of the raster layer. Trail conditions change rapidly and grade from 1m to the next could be quite different. And, the GPS error in the accuracy of the trail centerline versus transect point data adds to uncertainty in GIS layers.

Effect of Spatial Scale

Spatial scale, both the grain and the extent can influence the factors that we are trying to model. Rarer land cover types become lost as grain becomes more coarse (Turner et al.). To explore resolutions that would best suit the ecological problem we are modeling, several different resolutions for topography variables, at 1, 10 and 30m were explored. When considering what might be affecting erosion along the trail, spatial extent in which to frame the problem was considered. In the past, field studies had examined only the extent of trail transect. Slope and TSA were measured at the trail transect, with no regard for the conditions occurring uphill. This study, sought to explore the effects of spatial scale by framing trail erosion from a watershed perspective, both with the artificial tread watershed that the incised trail creates and the natural landform watershed. Variables that were significant to trail erosion came in and out of the model at different scales. For example, trail grade and TWI were both included in the model for the transect level, but they were not included in the final combined spatial scale model. This indicates that when one expands scope, variables that were important at a fine-scale can become less influential at larger scales.

The 5km segments have different topographic position, geology, hydrology, and main vegetation type. The final model explained 57% variance using a diversity of data, this shows that underlying factors such as slope, substrate type and precipitation are fairly universal over the three segments. Using a separate model for each segment could have increased the variance explained but then the model would have been very site-specific and not applicable over a diversity of landscapes within the northeastern United States.

Limitations

There are several limitations to the model. The GIS analysis relies on accuracy of the LiDAR-derived DEM; the raster DEM surface was interpolated from the classified LiDAR ground points. Interpolation introduces error because an algorithm is calculating the estimated elevation between data points of known elevation. The area between the data points could be over or underestimated. In addition, the data points themselves may not be accurate. The company that flew the LiDAR reported vertical accuracy within 18cm. LiDAR flown over very steep slopes is known to have greater inaccuracies than if flown over flatter terrain (Hodgson and Bresnahan 2004). The accuracy of the terrain affects the model because all of the terrain variables are calculated off of the DEM. Errors in elevation with produce errors with slope, curvature, and topographic roughness.

The higher spatial resolution DEM used in this model improved R^2 values of correlation to soil loss compared to other studies (Cakir 2005; Tomcyzk 2011), but the resolution still might not be sufficient. A trail makes quick turns and undulates up and down slopes. The spatial information that we calculate at 1m resolution may be too general for cases where the trail is making tight switchbacks or has drainage features. Tread drainage features are very important for moving water off the trail, but 1m data will not be able accurately reflect these features.

Because the soil loss measure was used to train the model, the assumption is that trail characteristics associated with transects that have very high soil loss will predict other spots that could erode greatly. However, soil loss may be recorded as slight even when trail characteristics such as slope and fall-line alignment predict substantial soil loss due to shallow depth to bedrock. In the study area's mountainous terrain the soils were very thin, often with only 2-5cm of soil over bedrock. In these situations, if the trail was steep and aligned with the fall-line, the erosion value could be small because the trail eroded quickly to a point where rock was exposed. This introduced error into the model because trail characteristics that should predict highly eroded trails will be trained to not point to high levels of soil erosion, causing the regressor to likely be insignificant. A measurement of mean soil depth to bedrock should have been included in the field data collection. In this case, the model is limiting because it cannot accurately predict the total net erosion but may be able to predict areas that will erode quickly. Whether those areas will be problem spots or not in terms of trail condition is another issue, directly tied to depth to bedrock since once bedrock is exposed the tread is stable and no longer causing environmental damage.

Another item that was not taken into consideration during field protocol development, was the type of organic litter on the trails. The measured segments of trail had either needle cover or broadleaf leaf cover. The needles are lighter, have less surface area and are more easily displaced by foot traffic. They do not protect the underlying trail tread soil as well as broadleaf leaves do. Broadleaf leaf litter intercepts raindrops more completely and increase infiltration rates, which can slow erosion rates.

Trail Management Implications

The development and design of official trails has long been thought of as an art. Many trail professionals, such as those in the U.S. Professional Trail Builders Association have a construction background and are adept at using mechanized and non-mechanized equipment to design and construct visually pleasing trails that are enjoyable to hike or bike. Trail science research has either been insufficient to inform the development of sustainable trail designs or has not been consulted. There is not a tradition of consulting trail science as there is in many other fields of professional land management (e.g., fish and wildlife management, recreation management). That is beginning to shift as standards established by the U. S. Forest Service and continuing trail science research by recreation ecologists on the environmental impacts of trails continue to ground the practice in science-based solutions. The focus now is on developing sustainable trails that work in harmony with the surrounding environment so that natural processes are used to the advantage of the trail system, and not the detriment.

It is possible for trails to be constructed and used for years with very little environmental impacts to vegetation, soil, and water. Trail design elements such as grade reversals, drainage dips, waterbars and capped switchbacks divert water off trails. Trail designers manage how frequently these elements are introduced to the trail depending on the topography and substrates the trail traverses. Slope, rockiness, alignment of the trail with the prevailing landform, and soil type all influence how a trail will resist degradation over time. Consideration of where water is entering the trail and where it is coming from influences how the trail will hold up over time. Taking a step back from the trail itself and looking at how the trail is a part of a larger system is critical to minimizing detrimental impacts. Adapting design standards to the type of ecosystem, topographic character and watershed character should all be a part of the process in designing good trails. To minimize environmental impacts, the trail must be designed in harmony with landscape, this means that not all trails should be designed the same, each one should be unique to meet the character of the landscape it is on. The "spatial scales combined" model presented in this paper offers insights for trail managers for environmental and trail design factors to consider when building sustainable trails.

Precipitation, mean trail corridor grade, substrate and steepness of the landform grade immediately surrounding the trail tread, along the trail corridor and for the upslope watershed were all significant factors in the "combined spatial scales" model at the 0.05 threshold. When trails are built in areas that receive a lot of rain, trail designers should put extra effort into designing and constructing sustainable trails that resist erosion. Key factors include maintaining a low average gradient from one rise to the next and maintaining out-sloped treads, or including an adequate density of tread drainage features.

Finally, we note that many A.T. treads within the study area have long since eroded to bedrock and have been stabilized for quite some time. A lack of correlation between mean tread depth and the various independent variables could be because these sections of tread are stabilized and can't continue to erode. Modeling results in these rocky areas would contrast with an area of deeper soils where substantial soil loss could occur, so the same type of erosional process, time, and use would yield substantially greater soil loss. This suggests that soil depth ought to be considered when making decisions about the need for relocations. A trail already eroded to bedrock is sustainable and could be retained, while an eroding trail in deeper soils should likely be closed and rerouted.

Conclusion

The regression modeling developed in this study predicts soil loss on unsurfaced trails with a higher level of accuracy than previous studies. In exploring three spatial scales and a final combined model using variables from all three spatial scales, we have identified some new soil loss relationships. GIS analyses with LiDAR data enabled the creation and use of both trail corridor and upslope watershed variables that have not been considered in other trail studies but which are significantly correlated to soil loss.

In the future, when variables in the model are accurately mapped, the model can be used to develop a map of soil erosion for the whole trail. As it stands, trail segments can only be mapped for areas that were already sampled in the study because mean grade and substrate type for the trail corridor, significant variables in the final model, were both collected in the field.

Future studies should acquire finer resolution LiDAR data at 0.5m or better for enhanced GIS layers at the transect and trail corridor scales. As fine resolution geospatial data becomes more readily available and technologies such as terrestrial LiDAR with 0.25m resolution become more affordable, an experimental study of trail erosion coupled with this technology would provide greater insights for relationships between topography, environmental factors and trail design characteristics that lead to tread soil loss. Additional testing of GIS surrogate data against data collected in the field is needed. Variables to be considered in future studies include depth to bedrock and the type of organic litter on the tread surface (leaf versus needle). The degree of out-slope should also be measured, as this may interact with the watershed landform and flow length variables.

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CHAPTER 5: CONCLUSION

Recreation managers can benefit from research that uses geospatial techniques to quantify changes in recreation resources. This dissertation applied geospatial and recreation ecology research techniques to investigate how recreation infrastructure changes over time. Visitors invariably impact soil and vegetation when they hike and camp in the backcountry. Quantifying long-term changes in these resource attributes can help managers to understand how to improve the sustainability of their recreation infrastructure. By preventing and minimizing environmental degradation managers ensure that visitors will have the same quality of experience in 100 years as they had today. Recreation planners and managers frequently seek out and apply Best Management Practices based on the best available science, such as presented in this dissertation, to fulfill the dual mandate of natural resource protection and recreation opportunity that guide most public land management agencies.

The first paper titled “Sustainable Campsite Management: Long-term Ecological Changes on Campsites in the Boundary Waters Canoe Area Wilderness, MN” (Chapter 2) focused on ecological changes at designated campsites, nodal areas of visitor impact caused by overnight camping activities. Examining the ecological change on campsites over the span of three decades can inform recreation managers on how to minimize detrimental environmental impacts from long-term visitation. Canoeing, camping and portaging through the lake systems in the Boundary Waters Canoe Area Wilderness is not only an allowed use, but a traditional historical and cultural use of the area. Maintaining the quality of experience without diminishing the natural resources or drastically limiting use is a goal of wilderness managers. This can only occur when the ecological integrity of the area is maintained. Camping contributes impacts to vegetation ground cover, tree cover, and soil. Minimizing these impacts so that campsites stay in good condition over time is critical to managing a wilderness area for the long term. The study presented in this dissertation reveals a significant decline in tree cover, an increase in the number of offsite “satellite” tenting areas, and increases in the area of exposed soil and ground vegetation cover. The ecology on campsites changed primarily due to the loss of campsite trees. This has caused a marked divergence between the campsites and the surrounding forests. Educational practices or regulations that discourage visitors from cutting trees will maintain tree cover and help campsites to blend in with the surrounding forest. Constructing side-hill campsites is an effective practice to minimize the footprint of impact from camping.

The second paper titled " "Naturalness" in Boundary Waters Canoe Area Wilderness, MN: Camping and Non-native Plant Ecology" (Chapter 3) discusses how wilderness quality has changed over 32 years of camping use, with a focus on the behavior of non-native plants located on campsites. Non-native plant cover did not change significantly over time, but the average number of non-native species found per campsite increased. This reveals that non-native plants are dispersing to more parts of the wilderness on campsites. Visitors are inadvertently transporting seeds of common weeds such as *Taraxacum offinicale, Plantago major* and *Trifolium repens* from their backyards, which are becoming established on wilderness campsites. How the presence and abundance of non-native plants influences wilderness character, where naturalness and untrammeling are protected values, is a dialogue and debate that should occur between wilderness managers and the public. The science presented in this dissertation documents longitudinal changes occurring over three decades. Once shaded campsites have become open and sunny, have increasing numbers of non-native plant species, and vegetation that contrasted sharply with the structure and composition of surrounding forests. The quality of wilderness character and what people will see and experience when they take a trip in the BWCAW in 1982, compared to 2014 or in future, is likely to be quite different. It is up to wilderness managers to apply relevant science to protect wilderness values and natural resources, ensuring that the area is protected for future generations. This will require the sustainable management of the recreation infrastructure so that visitation does not detrimentally harm the area's ecological integrity.

The third paper titled "Application of Airborne LiDAR in Modeling Trail Erosion along the Appalachian Trail, New Hampshire" (Chapter 4) examines the relationship between terrain characteristics and soil loss on this nation's most heavily visited National Scenic Trail. Soil loss is a primary resource concern because it is not easily reversible. This study applied geospatial analytical techniques to understand correlations between terrain characteristics and trail soil loss. Adjusted coefficients of determination were substantially higher than all previous studies, attributed primarily to new capabilities made possible by GIS software, LiDAR data, and analytical modeling conducted at multiple spatial scales. The integration of ground-based and GIS derived variables, and inclusion of new tread corridor and upslope landform watershed variables at differing scales enabled a significant increase in the predictive power of trail soil loss models.

It is recommended that recreation ecology research continue to expand and integrate the application of geospatial tools and analyses to aid in the discovery of more complex relationships between terrain variables and spatial patterns of use and impact. Geospatial technologies are rapidly expanding in their sophistication, availability, and resolution. The availability of high spatial resolution datasets can aid substantially in recreation ecology research, increasingly enabling the replacement of field-based measurements with GIS-derived measures. Geospatial techniques have the power to scale up fieldwork, for example, if a relationship is found between trail erosion and slope in one location, this relationship can be modeled over a trail that is thousands of miles long, such as the Appalachian Trail.

APPENDIX A

Boundary Waters Canoe Area Wilderness
Indicator Assessment Protocols

1) Site Number – Record original site number.

2) USFS BWCAW site number.

3) Measurement Date – Record the date, e.g., 6-5-14. If possible this should be within two weeks of the date the site was measured in 1982.

4) Lake Name: Name of the lake campsite is located on.

5) GPS Coordinate, site center. Also use Trimble unit to slowly walk the campsite boundaries. GPS datum:___________

6) Use level - An estimate of the number of nights of use per season the campsite receives (estimate provided by BWCAW backcountry managers familiar with the area). Generally the nearest 10 nights should be fine, if possible, or nearest 20.

7) Visibility - The visibility of the campsite from the water:

1 = Very visible - campsite or landing visible clearly visible from over 91 meters (100 yards).

2 = Moderately visible - campsite or landing visible from approximately 46 meters (50 yards).

3 = Barely visible - campsite or landing not visible until within 9 meters (10 yards) of shore.

4 = Not visible - campsite not visible from within a canoe, landing is completely natural.

8-11) Root Exposure - A rating system to be applied to each live tree (>2cm dbh) within the campsite boundaries, excluding those within undisturbed "islands" of vegetation and "satellite" use areas. Enclose tallies for dying trees in boxes.

1 = Root exposure no more than what is normal for the area (as compared to control site).

2 = Slight root exposure - the tops of many of the major roots exposed or more severe exposure on only 1 or 2 major roots.

3 = Moderate root exposure - the tops and sides of many of the major roots exposed or very severe exposure on only 1 or 2 major roots.

4 = Severe root exposure - the tops, sides and undersides of many of the major roots exposed.

12-15) Tree Damage - A rating system to be applied to each live tree (>2cm dbh) within the campsite boundaries, excluding those within undisturbed "islands" of vegetation and "satellite" use areas. Enclose tallies for dying trees in boxes.

1 = No tree damage (unless from natural causes).

2 = Slight tree damage - nails or nail holes, small branches cut or broken off, small superficial trunk scars or mutilations.

3 = Moderate tree damage - large branches cut or broken off, trunk scars and mutilations may be numerous but mostly small to moderate in size and totaling less than I square foot of trunk area.

4 = Severe tree damage - trunk sears and mutilations numerous with many that are large and having a combined total more than I square foot of trunk, any complete girdling of tree (including bark stripping all the way around the tree) regardless of areal extent.

16) Total Campsite Trees (#) - The sum of 9 or 10; the total number of trees (>2cm dbh) within the campsite boundaries, excluding those within undisturbed "islands" of vegetation and "satellite" use areas.

17) Sunlight - A rating system for assessing the campsite insolation.

1 = Full sunlight - little or no tree cover on site with full sunlight penetration to ground surface on a majority of the site.

2 = Moderate sunlight - tree cover present but for the most part sparse with moderate sunlight penetration to ground surface on a majority of the site.

3 = Low sunlight - moderate to dense tree cover over much of the site with partial sunlight penetration to ground surface.

4 = Complete shading - dense tree cover with little or no direct sunlight penetration to ground surface.

18) Site Expansion - A rating system for assessing potential campsite expansion.

1 = High - Off-site area is relatively level, free of large rocks, and has sparse vegetation and good drainage.

2 = Moderate - Off-site area is partially level and/or has some large rocks, moderate to dense vegetation, and poor drainage.

3 = Poor - Off-site area is mostly sloped (>8%) and/or has many large rocks, dense vegetation, and poor drainage.

4 = Very Poor - Off-site area is completely unsuitable for any campsite expansion due to steep slopes, rockiness, dense vegetation, and poor drainage.

19) Expansion, Limiting Factor - What is the single most limiting factor to campsite expansion for this site? 1=steep slopes, 2=rockiness, 3=dense woody vegetation, 4=poor drainage.

Site maintenance or rehabilitation work – record only when such work is visually evident/obvious. Check with USFS for record keeping on these activities to characterize their efforts over time, collect documentation and records – document by site # if possible. Also check/document amount of hazard tree removal and tree planting on sites, by site # if possible.

20) Site Maintenance – Canoe landing rockwork or logs. 0=not present, 1=present.

21) Site Maintenance – Tent pad improvement. 0=not present, 1=present.

22) Site Maintenance – Tent pad ruination, ice-berged rocks, depressions/mounds. 0=not present, 1=present.

23) Site Maintenance – Tree/shrub planting. 0=not present, 1=present.

24) Site Maintenance – Landing Closure/rehab work to prevent re-use. 0=not present, 1=present.

25) Landing Sites (#) – A count of the number of separate open canoe landing sites (must be separated by at least 10ft of relatively undisturbed vegetation/rock).

26) Other Campsites Visible (#): Record the number of other campsites, which if occupied, would be visible from the site or its shoreline accesses. This is a social variable to assess site intervisibility.

27) Landing Substrate – Record the predominant (>60%) landing area(s) substrate from the shoreline to within 1 vertical foot from water level. 1=bedrock, 2=loose rock or cobble, 3=soil, 4=sand, 5=combination (<60%).

28) Landing Erosion (in) – Average soil loss from sheet, rill, or gully erosion across the landing area(s) to the nearest inch based on assessments of tree root exposure or other evidence: 0, 1, 2, 3, ...

29) Landing Area Size (ft^2) – Geometric figure dimensions for the landing area for which soil loss was assessed.

30) Access Trail/Area Substrate – Record the predominant (>60%) access trail substrate, within 1 vertical foot from water's edge up to the beginning of the flatter campsite area. 1=bedrock, 2=loose rock or cobble, 3=soil, 4=sand, 5=combination (<60%).

31) Access Trail/Area Erosion (in) – Average soil loss from sheet, rill, or gully erosion across the access trail/area to the nearest inch based on assessments of tree root exposure or other evidence: 0, 1, 2, 3, …

32) Access Trail/Area Size (ft^2) - Geometric figure dimensions for the access trail/area for which soil loss was assessed.

33) Campsite Substrate – Record the predominant (>60%) campsite substrate for the remainder of the campsite, including satellite areas and excluding "islands" of undisturbed vegetation within the site boundaries. 1=bedrock, 2=loose rock or cobble, 3=soil, 4=sand, 5=combination (<60%).

34) Campsite Erosion (in) – Average soil loss from sheet, rill, or gully erosion across the campsite area to the nearest inch based on assessments of tree root exposure or other evidence: 0, 1, 2, 3, …

35) Campsite Size (ft^2) – Geometric figure dimensions for the remaining campsite area including satellite areas and excluding "islands" of undisturbed vegetation within the site boundaries.

36) Potential Tent Pads (#) – A count of the number of locations one could comfortably put up a 2-person tent within the campsite boundaries up to 6, with a >6 final category.

37) Satellite Areas (#) - The number of distinct satellite use areas (usually tenting areas) outside of the central campsite's primary boundary.

38) Informal Trails (#): A count of all trails leading away from the outer site boundaries, including landing trails, unless site merges with landing area. For trails that branch apart or merge together just beyond site boundaries, count the number of separate trails at a distance of 10 feet from site boundaries. Do not count extremely faint trails that have untrampled tall herbs in their tread.

39) Drainage - During normal weather conditions the campsite appears: 1 = wet, 2 = average, 3= dry

Note: Record exact percentages for indicators 40-45, which are defined to be mutually exclusive and sum to 100% relative to the total campsite area (#46). Include satellite use areas but exclude island areas.

40) Bare Ground (%) - Defined as ground where the mineral soil is largely exposed with little or no litter cover.

41) Sparse Ground Cover (%) - Defined as ground where non-tree plant cover is 5-50% in a $1m^2$ quadrat.

42) Dense Ground Cover(%) - Defined as ground where non-tree plant cover is 50-100% in a $1m^2$ quadrat.

43) Exposed Bedrock (%) - Defined as ground where bedrock is largely exposed with or without lichen and moss cover.

44) Exposed Root Area (%) - Defined as ground where tree roots are exposed (Root Exposure categories 2-4) as well as the adjacent areas between them.

45) Litter Cover (%) - Defined as ground where non-tree plant cover is less than 5% in a $1m^2$ quadrat and which is not bare mineral soil or exposed bedrock.

46) Total Campsite Area (ft^2) - The total area of the campsite, including satellite areas and excluding “islands” of undisturbed vegetation within the site boundaries. Examine the 1982 diagram and assess only those same “use areas” assessed in that survey (note that the 1982 survey sometimes excluded measurements of the landing area and access trails). Mark this area with flagging so that parameters 40-45 and 47-55 will be assessed as percentages of this area.

Note: For indicators 47-55 us the following percentage classes:
1 = 0% or NA, 2 ≤1%, 3 = 2-5%, 4 = 6-25%, 5 = 26-50%, 6 = 51-75%, 7 = 76-100%

47-51) Vegetative Cover (%) - Separate estimates of the tree, shrub, herb/grass, and moss/lichen cover for the campsite using the cover percentage classes listed in # 46 above.

51-55) Vegetative Strata (%) - Separate estimates of the strata >20m, 9-20m, 2-9m, 0.5-2m, <0.5m for the campsite using the cover percentage classes listed in #45 above.

56) Condition Class (Frissell) rating:

1 – Ground vegetation flattened but not permanently injured. Minimal physical change.
2 – Ground vegetation worn away around fireplace or center of activity area.
3 – Ground vegetation lost on most of the site, but humus and litter still present in all but a few areas.
4 – Bare mineral soil widespread. Tree roots exposed on the surface.
5 – Soil erosion obvious. Trees reduced in vigor or dead.

57) Standing Dead (#) - The total number of standing dead trees (>2 cm dbh) within the campsite boundaries, excluding those within undisturbed "islands" of vegetation and including those on "satellite" use sites. Enclose tallies for trees with tree damage categories 3 or 4 in circles, enclose tallies for trees with root exposure 3 or 4 in boxes, and enclose tallies with both in triangles. This additional information will be analyzed separately and will not be entered under parameter #58.

58) Stumps (#) - The total number of stumps of any diameter within the campsite boundaries, including those within undisturbed "islands" of vegetation and on "satellite" use sites. Tally and record the total number of stumps for this indicator.

59) Tree Seedlings, Camp (#) - The number of tree seedlings between 6 and 55 inches within the campsite boundary, excluding those within undisturbed "islands" of vegetation and including those on "satellite" use sites, will be tallied and the total entered for this parameter.

60) Tree Seedlings, Islands (#) - The number of tree seedlings between 6 and 55 inches within undisturbed "islands" of vegetation within the campsite boundary, will be tallied and the total entered for this parameter.

61) Tree Saplings, Camp (#) – The number of tree saplings between 56 inches tall up to a dbh of 2 cm within the campsite boundary, excluding those within undisturbed "islands" of vegetation and including those on "satellite" use sites, will be tallied and the total entered for this parameter.

62) Tree Saplings, Islands (#) – Tally the number of tree saplings between 56 inches tall up to a dbh of 2cm within undisturbed "islands" of vegetation within the campsite boundary, will be tallied and the total entered for this indicator.

63) Offsite Tree Damage (#) – Assess and tally trees with damage ratings of 3 or 4 within undisturbed "islands" of vegetation and in adjacent offsite areas, including "satellite" use areas. Apply the same ratings used for assessing campsite trees but limit tallies to those rated a 3 or 4 for damage. Limit your search to adjacent areas where individuals using this particular campsite would typically go to obtain firewood; do not conduct intensive searches far away from the area.

64) Offsite Tree Stumps (#) - Same as above for tree stumps, conducted simultaneously.

65) Bear Bag Impacts – A rating system to assess the extent of resource impacts from bear bag hanging. Assess tree branch damage onsite and in adjacent off-site areas, using judgment to determine if damage is likely to be from bear bag hanging activity. Assess clearly visible trampling damage to vegetation and soils primarily in offsite areas unless clearly related to bear bag hanging and damage is greater than adjacent campsite areas.

1 – No to minimal evidence of damaged/broken/dead branches or trampling damage.
2 – A few damaged/broken/dead branches (1-3) evident and/or some trampling damage.

3 – Many damaged/broken/dead branches (4-6) and moderate amounts of trampling damage.
4 – A large number of damaged/broken/dead branches (>6) and considerable amounts of trampling damage.

66) Average Thickness of Organic Horizon (cm) - An average of 10 measurements (in cm) taken in randomly selected central campsite locations.

67) Average Compaction (kg/cm^2) - An average of 10 measurements taken with a soil pocket penetrometer in randomly selected central campsite locations.

68) Bulk Density (g/cm^3) - Bulk density measure calculated from excavated soil samples from four randomly selected locations within the central "core" area of each campsite.

<u>Bulk Density Procedures</u>
The irregular-hole method (Howard and Singer, 1981) will be used for determining bulk density. The procedure for this method is as follows:

1) Surface organic horizons are removed and the soil surface is leveled,
2) A hole approximately 5x5x8 cm is excavated and all soil removed is saved in a labeled airtight plastic bag.
3) The hole is lined with plastic (Saran Wrap) and filled with water from a graduate cylinder until the meniscus is level with the leveled soil surface.
4) The volume of water required to fill the hole is recorded at the base of the physical site data form.
5) A subsample from the four soil samples is dried in an oven at 105°C and weighed.
6) The soil moisture value is extrapolated to the total "wet" weights recorded and bulk density is calculated (g/cm^3).

Place the soil excavated from the four holes into a common container but record the volume of water for each sample separately (the cylinder could be tipped over…). Weigh and record the entire soil container, removing the tare weight of the container. Then thoroughly mix the soil and extract a subsample (about a 1 inch cube in size) and record the subsample weight (these will be dried and reweighed in the lab). Place the subsample in a ziplock plastic bag labeled with the campsite number and as "Campsite" and store in a larger gallon sized freezer ziplock.

69) Soil Moisture (%) – Calculated as the difference between the field "wet" weight and the lab "dry" weight.

Photographs – Take photos of the campsite from offsite, of the landing area, access trail area, and campsite area (1 or 2 if needed to capture the entire area). Representative examples of tree damage, root exposure, fire rings, and other impacts are also useful, as are photos of staff taking measurements. Label these by referencing the unique photo date/time/# information. Record this and related comments on the form for the campsite.

Control Site Form

Same as for campsite for those indicators included.

Vegetative Data Form

Each species will first be listed under the appropriate heading: trees, shrubs, herbs (including grasses, sedges, and ferns), and mosses & lichens. If identification is not certain a plant specimen will be removed and pressed in a field plant press. Each plant specimen will be assigned an identification number which will be used to label that particular species until it is identified. Following the listing of species a cover estimate will be recorded for each of the listed species. The following coverage classes (after Braun-Blanquet, 1965) will be used with reference to the total campsite area, excluding undisturbed "islands" of vegetation:

7 = Any number, with cover more than 3/4 of the reference area (>75%)
6 = Any number, with 1/2 to 3/4 cover (50-75%)
5 = Any number, with 1/4 to 1/2 cover (25-50%)
4 = Any number, with 1/20 to 1/4 cover (5-25%)
3 = Numerous, but less than 1/20 (5%) cover, or scattered, with cover up to 1/2O
2 = Few, with small cover
1 = Solitary, with small cover

Scale values 2-5 refer only to cover, defined as the vertical projection of the crown or shoot area of the species to the ground surface and expressed as a fraction or percent of the campsite area. The lower three scale values are primarily estimates of abundance, the number of individuals per species.

The appropriate number (1through 7) will be placed on the form for each species and the same procedure will be repeated on the control site. Additional species will be added and some of the campsite species will most likely be absent from the control. The 5 strata categories are a duplication of those which appear on the physical site data form.

Bibliography

Braun-Elanquet, J. 1965. Plant Sociology: The Study of Plant Communities. (Transl., ed., and rev. by C.D. Fuller and H.S. Conrad) Hafner, London. 439pp.

Grigal, D.F. and L.F, Ohmann. 1975. Classification, description, arid dynamics of upland plant communities within a Minnesota wilderness area. *Ecological Monographs* 45:389-407 b

Howard, R.F. and N.J. Singer. 1981. Measuring forest soil bulk density using irregular hole, paraffin clod, and air permeability. *Forest Science* 27(2):316-322.

Boundary Waters Canoe Area Wilderness Campsite Data Form

1) 1982 Site Number		36) Potential Tent Pads (0 … 6, >6)	
2) USFS Site Number		37) Satellite Areas (#)	
3) Measurement Date		38) Informal Trails (#)	
4) Lake Name		39) Drainage (1=Wet, 2=Avg, 3=Dry)	
5) GPS Coordinate		1=0% 2=1 3=1-5 4=5-25 5=25-50 6=50-75 7=>75)	
6) Use Level		40) Bare Ground (%)	
7) Visibility (1=100 yds, 2=50, 3=10, 4=Not Vis)		41) Sparse Veg Ground Cover (%) (5-50%)	
8) Root Exposure 1 ___		42) Dense Veg Ground Cover (%) (50-100%)	
9) Root Exposure 2 ___		43) Exposed Bedrock (%)	
10) Root Exposure 3 ___		44) Exposed Root Area (%) (Root Ex 2-4)	
11) Root Exposure 4 ___		45) Litter Cover (%)	
12) Tree Damage 1 ___		46) Campsite Area based on 1982 diagram	
13) Tree Damage 2 ___		47) Tree Cover (%)	
14) Tree Damage 3 ___		48) Shrub Cover (%)	
15) Tree Damage 4 ___		49) Herb/Grass Cover (%)	
16) Total Campsite Trees (#)		50) Moss/Lichen Cover (%)	
17) Sunlight Rating (1=Full … 4=Complete Shade)		51) Veg Strata >65 ft (%)	
18) Site Expansion (1=High, 2=Mod, 3=Poor, 4=V Poor)		52) Veg Strata 30-65 ft (%)	
19) SE Limiting F (1=Slope, 2=Rock, 3=W Veg, 4=Wet)		53) Veg Strata 6.6-30 ft (%)	
20) Maint: Landing Rocks/Logs Added (0/1)		54) Veg Strata 1.6-6.6 ft (%)	
21) Maint: Tent Pad Improvement (0/1)		55) Veg Strata <1.6 ft (%)	
22) Maint: Tent Pad Ruination (0/1)		56) Condition Class (1=Minimal … 5=Severe)	
23) Maint: Tree/shrub Planting (0/1)		57) Standing Dead (#) ___	
24) Maint: Landing Closure (0/1)		58) Stumps (#) ___	
25) Landing Sites (#)		59) Tree Seedlings, camp (#) ___	
26) Other Campsites Visible (#)		60) Tree Seedlings , islands (#) ___	
27) Landing Substrate (1=Bedr, 2=R, 3=S, 4=Sa, 5=C)		61) Tree Saplings, camp (#) ___	

28) Landing Erosion (avg, inch)		62) Tree Saplings, islands (#)	
29) Landing Size (Dimensions, ft)		63) Offsite Tree Damage (#)	
30) Access Trail/Area Substrate		64) Offsite Tree Stumps (#)	
31) Access Trail/Area Erosion (avg, inch)		65) Bear Bag Impact Rating	
32) Access Trail/Area Size (ft^2)		66) Avg Thickness of Organic Horizon (cm)	
33) Camp Subst (1=Bedr, 2=R, 3=S, 4=Sa, 5=C)		67) Avg Compaction (kg/cm^2)	
34) Campsite Erosion (avg, inch)		68) Bulk Density (g/cm^3), lab	
35) Campsite Size (ft^2) (Dimensions, ft)		69) Soil Moisture (%), lab	

Standing Dead	Photographs (date/time/comment)	Org. Horiz (cm)	Compaction	H_20 Vol (ml)	Soil Wgt (g)
		1)	1)	1)	1)
		2)	2)	2)	2)
		3)	3)	3)	3)
		4)	4)	4)	4)
		5)	5)		
		6)	6)	Subsample Wgt (g)	
= T Dam 3/4		7)	7)	1)	
= Root Ex 3/4			8)		
		8)			
= Both 3/4		9)	9)		
		10)	10)		

Control Form

70) Sunlight Rating (1=Full … 4=Complete Shade)	
1=0% 2=1 3=1-5 4=5-25 5=25-50 6=50-75 7=>75)	
71) Bare Ground (%)	
72) Sparse Veg Ground Cover (%) (5-50%)	
73) Dense Veg Ground Cover (%) (50-100%)	
74) Exposed Bedrock (%)	
75) Exposed Root Area (%) (Root Ex 2-4)	
76) Litter Cover (%)	
77) Campsite Area based on 1982 diagram	
78) Tree Cover (%)	
79) Shrub Cover (%)	
80) Herb/Grass Cover (%)	
81) Moss/Lichen Cover (%)	
82) Veg Strata >65 ft (%)	
83) Veg Strata 30-65 ft (%)	
84) Veg Strata 6.6-30 ft (%)	
85) Veg Strata 1.6-6.6 ft (%)	
86) Veg Strata <1.6 ft (%)	
87) Standing Dead (#)	
88) Stumps (#)	
89) Tree Seedlings (#)	
90) Tree Saplings (#)	
91) Avg Thickness of Organic Horizon (cm)	
92) Avg Compaction (kg/cm^2)	
93) Bulk Density (g/cm^3), lab	
94) Soil Moisture (%), lab	

General comments about the campsite/control:

Standing Dead		Org. Horiz (cm)	Compaction	H_20 Vol (ml) Soil Wgt (g)	
		1)	1)	1)	1)
		2)	2)	2)	2)
		3)	3)	3)	3)
		4)	4)	4)	4)
		5)	5)		
		6)	6)	Subsample Wgt (g)	
= T Dam 3/4		7)	7)	1)	
= Root Ex 3/4		8)	8)		
= Both 3/4		9)	9)		
		10)	10)		

BWCAW Campsite Vegetative Data Form

Site # ___________

Cover Categories: 1 = Solitary/small cover, 2 = Few, small cover, 3 = Numerous, 2-5%, 4 = 6-25%, 5 = 26-50%, 6 = 51-75%, 7 = 76-100%

Species	Camp	Control	Species	Camp	Control
Trees			8)		
1)			9)		
2)			10)		
3)			11)		
4)			12)		
5)			13)		
6)			14)		
7)			15)		
Total % Cover			16)		
			17)		
Shrubs			Total % Cover		
1)					
2)			Mosses/Lichens		
3)			1)		
4)			2)		
5)			3)		
6)			4)		
7)			5)		
8)			Total % Cover		
Total % Cover					
			47) Tree Cover (%)		
Herbs/Grasses			48) Shrub Cover (%)		
1)			49) Herb/Grass Cover (%)		
2)			50) Moss/Lichen Cover (%)		
3)			51) Veg Strata >65 ft (%)		
4)			52) Veg Strata 30-65 ft (%)		
5)			53) Veg Strata 6.6-30 ft (%)		
6)			54) Veg Strata 1.6-6.6 ft (%)		
7)			55) Veg Strata <1.6 ft (%)		

APPENDIX B

Trail Assessment Protocols
Appalachian Trail

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 and along trail corridors. All data was recorded using Apple IPads in the field with Qualtrics mobile off-line app. Measurements will document the trail's width, depth, substrate, slope, alignment and other characteristics.

Assessments were taken in June, near the middle or end of the visitor use season but before leaf fall. 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.

Materials

☐Day pack with extra clothing, rain gear, lunch/snacks, water, water filter, hat, sunscreen, first aid kit, phones, car key, fanny pack w/filled water bottles, trash bags to cover packs in rain, other?
☐ Topographic maps and manual on waterproof paper
☐ iPad w/charged battery & connector cord for power bank
☐ Trimble GeoXH GPS w/charged battery, stylus, and data dictionary. Loaded with A.T. corridor, treadway, and the Informal Trail data dictionary. Zephyr dome antennae w/pole and wire connector where needed to pull in signals under tree canopies. Spare battery and connector wire if needed.
☐ Garmin 64 GPS unit w/charged & spare batteries loaded with the A.T. study segment endpoints and sample (transect) points
☐ Panasonic Lumix digital camera w/charged & spare batteries
☐ Pin flags, large washers w/flagging tape, chalk for marking transects
☐ Backup field forms on small clipboard
☐ Flexible transect line tape measure in centimeters (5m retractable)
☐ Tape measure for CSA depths in millimeters (16 ft retractable)
☐ Small notebook and pens, pencils
☐Tent stakes (4)
☐Metal binder clips (4) to attach tape to stakes
☐ Compass/clinometer combo
☐Power bank and cords

Point Sampling Procedures

Trail Segment Info: 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 in the Segment form on the iPad or on separate paper.

Use Level (UL): 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.

Segment ID: Record the trail segment ID number.

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

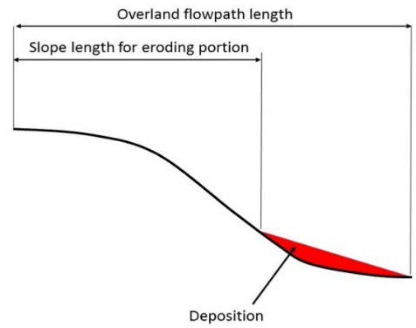
Date: Record the date (mm/dd/yr) the trail was surveyed.

Inventory Indicators

Using a Garmin 64 GPS unit, look up Tracks and choose the next study segment. Show it on the map and look for the closest A.T. parking location or road crossing. If needed call Matt or Claire for additional access guidance and advice (or assistance). Select the parking lot or road crossing and "Go To" to navigate there with the City Navigator map enabled (w/Map showing press Menu button and Setup Map). When you arrive turn off the City Navigator map in the Setup menu and enable the topo map, then select the first transect you want to measure (note, the Topo map will not show if City Navigator is enabled). Select "Go To" and navigate to a location that is at or exactly perpendicular to the sample point. Start the transect measurements. Place the Trimble at the center of the transect to record an averaged waypoint while conducting assessments, saving it when done and named with the 5-digit trail segment/transect number.

Assess A.T. tread conditions at every sample point – no rejections are permitted even if a sample point occurs in a creek, on a road, or at other odd locations. 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," just leave the entry blank.

1) **Trail Segment/Transect:** Record a combined trail segment and transect number (5 digits).



2) **Upslope Trail Grade (TG):** The two field staff should position themselves on the transect and about 3m (10 ft) in an uphill direction **along (on) the trail** from the transect. Use the clinometer to determine percent 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 percent.

3) **Landform Grade (LG):** The two field staff should position themselves at the transect and about 3m in an uphill direction along the fall line from the point. Your objective is to measure the prevailing landform grade in percent slope in the vicinity of the transect. A single person method can be utilized: walk up-fall-line approximately 3m, place a flag around a tree bole at your eye-level when standing adjacent to the tree (on the contour and on "average" landform i.e. not in a hole or perched on a rock/log), walk down fall line to the lowerside of the trail (again, on "average" landform) and shoot a percent grade with your clinometer to the flag, record this value [You can also locate a branch or other "landmark" along a tree or rock at eye-level eliminating the need to walk up and gather the flagging].

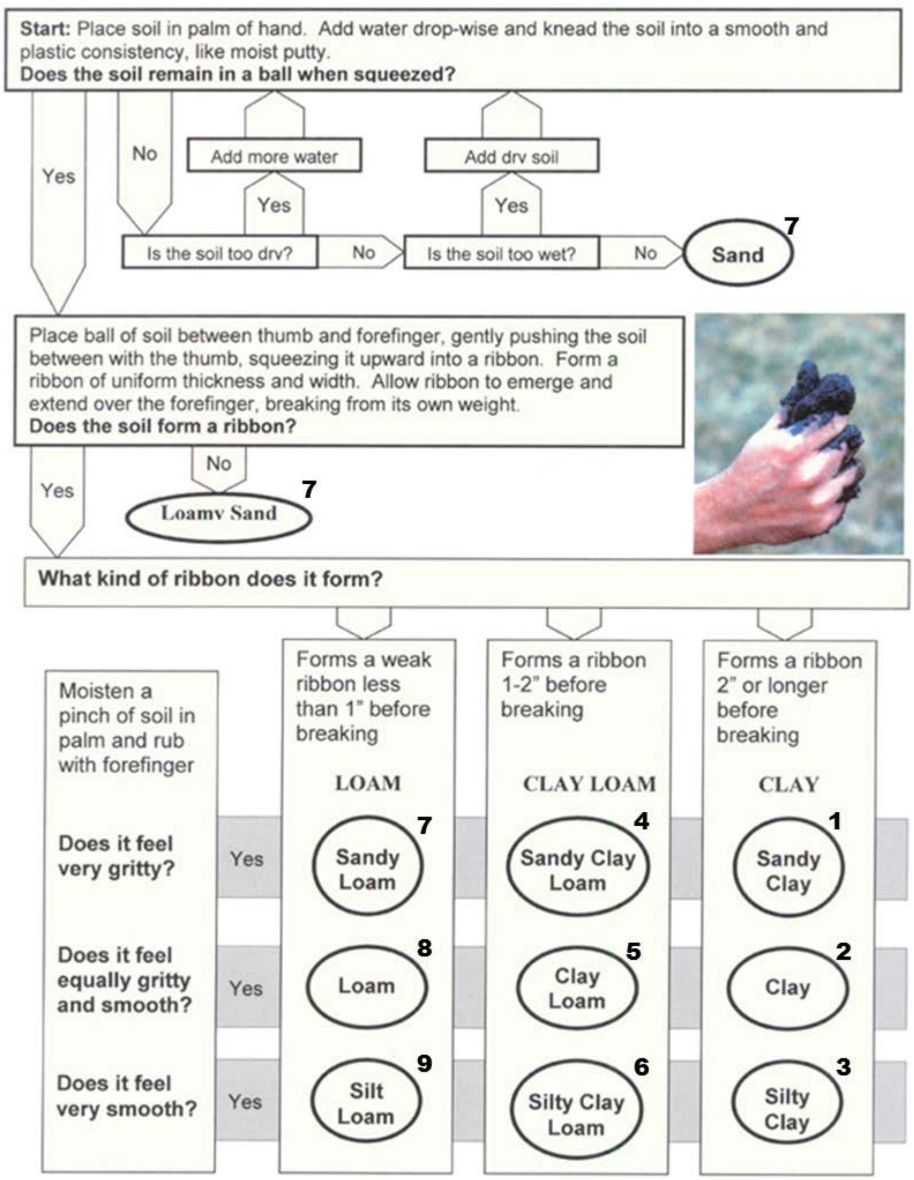
4-5) **Trail Slope Alignment Angle (TSA):** Looking uphill from the sample point, identify and project the fall-line across the A.T. Choose the direction along the A.T. that makes an acute angle (<90^o) with the fall line. Sight the peep-hole compass along the A.T. in the acute angle direction (3m segment) and record as "Trail^o" the compass azimuth. Use the top numbers visible in the compass (bottom numbers are the back azimuth). Repeat to assess and record the azimuth of the fall line as "Fall Line^o". The Trail Slope Alignment angle (<90^0) will be computed by subtracting the smaller from the larger azimuth (computed after data entry).

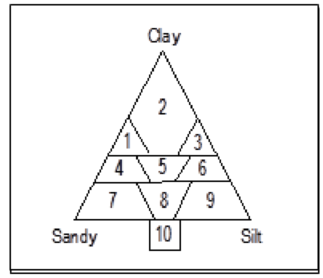
Trail Slope Alignment (TSA)	Degradation Potential	Trail Profile
0-22°	**Very High** – tread drainage rarely possible; erosion, widening, & muddiness probable	
23-45°	**High** – tread drainage is often difficult; erosion, widening, & muddiness are likely	
46-68°	**Low** – tread drainage is possible; low potential for problems	
69-90°	**Very Low** – tread drainage is easy; very low potential for problems	

6) **Soil Texture (TX):** 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). Check the texture without wetting at the sample points and repeat the full method if it appears to have changed. Use the scraper to excavate soil about the size of a golf ball (1.5 inches).

Record a classification:

Soil Texture by Feel





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

10 - Black Organic Soil

11 - Sand

7) **Erosion/Deposion (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 erosion or deposition, including transects with substantial rock, boardwalk, gravel, etc.

8) **Upper Trail Transect Watershed Boundary (UTWB):** Walk in an uphill direction from the trail transect until you reach a point where some of the water running down the trail during a sizable rainstorm would flow off the trail. This may due to a human-constructed water bar or drainage dip, a natural feature (e.g., tree root, rock, or dip), tread out-sloping, or where the tread would no longer carry water due to loose rock. Record a 1-minute averaged waypoint at this location labelled with the transect number for the most recent transect followed by the letter "a" and an estimate of what percentage of water would flow off (nearest 10%). If this percentage is 100% stop and complete indicator 9 as well, otherwise continue walking until the next location where water runs off and repeat the procedure (including indicator 9). Continue identifying these features until you reach a location where 100% of the water would flow off, assess indicator 9 and then move on to indicator 10.

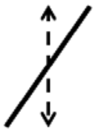
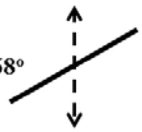
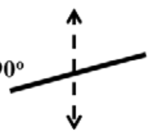
9) **Drainage Feature Type (DT):** Record the type of drainage feature at the UTWB: a) Wood water bar, b) Rock water bar, c) Drainage dip, d) Grade reversal (natural or man-made), e) Tread out-sloping, f) Natural rocks, g) Exposed roots, h) Other.

10) **Trail Transect "Watershed" Tread Width (TWTW):** As you walk from the transect uphill to the UTWB periodically measure the tread width and at the end identify the nearest even hundred mm category for average tread width, e.g., 200, 400, 600, …

11) **Trail Transect "Watershed" Trail Grade (TWTG)**: As you walk from the transect uphill to the UTWB periodically measure the trail grade and record the average value (alternately if you can see the UTWB from the Transect, shoot the grade with either the two person or single person methods outlined in item #2: Trail Grade.

12) **Trail Watershed TSA (TWTSA)**: As you walk from the transect uphill to the UTWB periodically estimate the trail slope alignment angle and at the end enter an "average TSA" for the tread watershed: a) 0-22 (fall-line alignment, b) 23-45, c) 46-68, d) 69-90 (contour alignment). See figure below.

13) **Erosion Type (ET):** Assess and record soil erosion at the sample point, if present (see definitions in #20). **N –** No erosion evident, **RE –** Recent erosion, **HE –** Historic erosion

Trail Slope Alignment (TSA)		Degradation Potential	Trail Profile
0-22°		**Very High** – tread drainage rarely possible; erosion, widening, & muddiness probable	
23-45°		**High** – tread drainage is often difficult; erosion, widening, & muddiness are likely	
46-68°		**Low** – tread drainage is possible; low potential for problems	
69-90°		**Very Low** – tread drainage is easy; very low potential for problems	

14) **<u>Trail Watershed Tread Groundcover (TWTG)</u>**: As you walk from the transect uphill to the UTWB periodically assess the groundcover and at the end enter "average groundcover" values for any category below where the cover is ≥20%. What intercepts the raindrops and impedes surface runoff.

S-Soil	All soil types excluding organic muck.
O-Organic	Dark organic soils (wet or dry).
L-Litter	Organic litter (leaves, needles, small sticks)
RS-Rock	Smaller rock (<5cm); natural or human-placed.
RM-Rock	Moderate sized rock (6-30cm)
RL-Rock	Large rock (>30cm)
B-Bedrock	Bedrock
RT-Roots	Exposed tree or shrub roots.
V-Vegetation	All ground vegetation types, including moss and grasses.
WO-Wood	<u>Human-placed</u> wood (water bars, bog bridging, cribbing).

15) **<u>Trail Watershed Tread Substrate (TWTS)</u>**: As you walk from the transect uphill to the UTWB periodically assess the substrate and at the end enter "average substrate cover" values for any category below where the cover is ≥20. What substrates are underneath vegetation and litter cover and how permeable are they.

S-Soil	All soil types excluding organic muck.
O-Organic	Dark organic soils (wet or dry).
RS-Rock	Smaller rock (<5cm); natural or human-placed.

RM-Rock	Moderate sized rock (6-30cm)
RL-Rock	Large rock (>30cm)
B-Bedrock	Bedrock
RT-Roots	Exposed tree or shrub roots.
WO-Wood	Human-placed wood (water bars, bog bridging, cribbing).

16) **Upslope Landform Watershed Groundcover (ULWS)**: As you walk from the transect uphill to the UTWB periodically assess the groundcover of the land upslope of the trail. Enter "average groundcover" values for each category below where the cover is ≥20%. This assesses the surface that is hit by falling raindrops and the surface rugosity that impedes runoff.

S-Soil	All soil types excluding organic muck.
O-Organic	Dark organic soils (wet or dry).
RS-Rock	Smaller rock (<5cm); natural or human-placed.
L-Litter	Organic litter (leaves, needles, small sticks)
RM-Rock	Moderate sized rock (6-30cm)
RL-Rock	Large rock (>30cm), including bedrock
B-Bedrock	Bedrock
RT-Roots	Exposed tree or shrub roots.
V-Vegetation	All ground vegetation types, including moss and grasses.

17) **Upslope Landform Watershed Substrate (TWTS)**: As you walk from the transect uphill to the UTWB periodically assess the substrate of the upslope watershed and at the end enter "average substrate cover" values for any category below where the cover is ≥20. What substrates are underneath vegetation and litter cover and how permeable are they.

S-Soil	All soil types excluding organic muck.
O-Organic	Dark organic soils (wet or dry).
RS-Rock	Smaller rock (<5cm); natural or human-placed.
RM-Rock	Moderate sized rock (6-30cm)
RL-Rock	Large rock (>30cm)
B-Bedrock	Bedrock
RT-Roots	Exposed tree or shrub roots.
WO-Wood	Human-placed wood (water bars, bog bridging, cribbing).

18) **Upslope Landform Watershed Grade (TTWLG)**: As you walk from the transect uphill to the UTWB periodically measure the landform grade of the land immediately upslope of the

trail. This is the "trail watershed." At the end enter identify nearest 5 degree value for average trail grade, e.g., 0, 5, 10, 15…

19) **<u>Roadbed:</u>** Is the trail on an old roadbed? Y/N
20) **<u>Drainage Ditch:</u>** Is there a drainage ditch on the upslope side of the tread? Y/N

Impact Indicators

Transect Establishment: Placement of the transect stakes and line require a great deal of judgment based on a variety of factors as soil loss will be measured from your configuration of these items. Measured soil loss includes erosion by water or wind, soil displacement from trail users, and soil compaction.

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 organic litter and/or soils. 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. The movement of soil 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 measures of soil loss following construction.

Recent vs. historic erosion: Recent erosion, i.e. erosion that has occurred within the active trail tread (see Figure 2) is what has been recorded in many recreation ecology studies. This study uses historical erosion, the net soil loss experienced along the trail from after it was first built to current conditions.

a) <u>Direct-ascent trails w/historic erosion</u>: Refer to Figure 2b – if you judge that some of the erosion is historic then follow these procedures. Generally you will find an eroded tread within a larger erosional feature. Place two stakes and stretch the transect line to reflect and allow measurements of the more recent recreation-related erosion (if present).

b) <u>Side-hill trail</u>: Refer to Figure 2c. The objective of this option is to place the transect stakes and line to simulate the post-construction pre-use tread surface, thereby focusing measuresments on post-construction soil loss. When side-hill trails are constructed, soil on the upslope side of the trail is removed and deposited downslope to create a gently out-sloped bench (most agency guidance specify a 3-5% outslope) for the tread surface (see Figure 2). 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 compaction, displacement and erosion. The extent of this incision are what these procedures are designed to estimate.

Carefully study the area 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 if roots 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 tread surface. Note that sometimes a raised berm of soil, organic material and vegetation will form on the downslope side of the trail that is raised slightly above the post-construction tread surface. If present, place the stake and line below the height of the berm based on your best judgment as shown in Figure 2c so that it does not influence your measurements.

d) <u>Side-hill trail with historic erosion</u>: Refer to Figure 2d - if you judge that the erosion is historic then follow these procedures. Generally you will find an eroded tread within a larger erosional feature. Place two stakes and stretch the transect line to reflect and allow measurements of the more recent recreation-related erosion (if present).

From the sample point, extend a line transect <u>*perpendicular*</u> to the trail tread. Identify the endpoints of this trail tread transect 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, or, when vegetation cover is reduced or absent, changes in organic litter (intact vs. pulverized) (see photo illustrations in Figure 1 at the end of this document). 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 necessary it is appropriate to examine the adjacent 2 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 of mostly undisturbed vegetation or organic litter.
- If the trail is on rock steps use the width of rock steps unless there is visible evidence of walking on bordering rocks or around them.
- If the trail is on a boardwalk include only the width of the boardwalk unless there is visible evidence of walking on adjacent soils/rocks. If the adjacent disturbed area is standing water or muddy include it because it likely receives traffic during drier times.
- 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. It's also appropriate to take into account transect topography, i.e., where visitors are most likely to walk or not walk. If one or both boundaries are still guesswork then leave tread width and CSA blank. Also leave this blank if the trail is on any type of pavement or a gravel road, in a creek, etc.

Pay close attention to selecting boundary points that reflect the extent of soil loss representative for this location along the trail. Insert the first stake by hammering it in at a slight outward angle so that the "0" mark on the end of the tape is directly above the right trail boundary, then hammer in the other stake at the opposite boundary, also at a slightly outward angle. Hook the tape end on the first stake so that the 0 mark is at ground level at the right trail boundary, stretching the tape between the stakes and wrapping it around the second stake. If the tape is unobstructed by rocks or roots pull it tight and attach a binder clip. The tape should be touching the ground surface at the 0 mark and at the second stake. If there are obstructing rocks or roots elevate the tape on both ends <u>*the same number of centimeters*</u> such that the tape clears the obstructions. Ideally the tape should be sufficiently tight that it pulls the two stakes vertical (perpendicular to the ground) before attaching the binder clip. Any bowing in the middle of the tape will bias your measurements (use rocks or other field staff to position the line in rocky areas when needed). Soil loss measures are taken from this line to the trail tread so the line should reflect your best judgement of post-construction pre-use soil loss.

***Take a photo of the Trail Transect with tape line in place.** Capture both stakes and the tread under the line with some foreground and background included so that a future surveyor could replicate your transect if needed. Record the photo number on the iPad.

21) **Secondary Treads (ST):** Count the number of braided trails, regardless of their length, that closely parallel the main tread at the sample point. *Do not count the main tread.*

22) **Tread Width (TW):** Measure and record the length of the transect (tread width) to the nearest millimeter).

23) **Transect Line Offset (TLO):** If needed to elevate the transect tape an equal distance (nearest centimeter) on both stakes above obstructing roots or rocks.

24) **Cross-Sectional Area (CSA):** The objective of the CSA measure is to measure trail soil loss from the estimated post-construction tread surface to the current tread between the trail boundaries. Note that in some areas soil deposition may have occurred. In these areas place the transect line flat on the ground so that CSA is 0. *End the final vertical measure by including a period after the number*. Do not assess CSA for boardwalks, any type of pavement, or any road w/vehicle use.

    Measurement Procedure: Starting on the left side enter the incision below the 10cm mark first (V_2 in Figure 2a-d), then the 20 cm mark and so on until you reach the far side of the trail and the last incision measure before the final 0 incision is reached at the stake. The standard interval for these measures is 100 mm (10 cm). Take all vertical measures *perpendicular* to the transect line down to the ground surface recording values to the nearest millimeter using the retractable tape measure (e.g., 260mm or 265mm). Enter the values next to their labeled numbers (e.g., V_2, $V_3 \ldots V_n$)

25) **Maximum Incision (MI):** Select and measure along the transect line the maximum incision value, recorded to the nearest millimeter using the retractable tape measure (e.g., 260mm or 265mm).

26) **Transect Line Slope, Current:** Record the slope of the transect line in degrees.

27-36) **<u>Tread Condition Characteristics:</u>** Along a 20 cm wide band centered on the trail tread width 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%**.

S-Soil:	All soil types including sand and organic soils, excluding organic litter unless it is highly pulverized and occurs in a thin layer or smaller patches over bare soil.
L-Litter:	Surface organic matter including intact or partially pulverized leaves, needles, or twigs that mostly or entirely cover the tread substrate.
V-Vegetation:	Live vegetative cover including herbs, grasses, mosses rooted within the tread boundaries. Ignore vegetation hanging in from the sides.
R-Rock:	<u>Naturally-occurring</u> 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.
M-Mud:	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.
G-Gravel:	<u>Human-placed</u> (imported) gravel.
RT-Roots:	Exposed tree or shrub roots.
W-Water:	Portions of mud-holes with water or water from intercepted seeps or springs.
WO-Wood:	<u>Human-placed</u> wood (water bars, bog bridging, cribbing).
O-Other:	Specify.

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 (>95%) of traffic, selecting the most visually obvious boundary that can be most consistently identified by you and future trail surveyors.

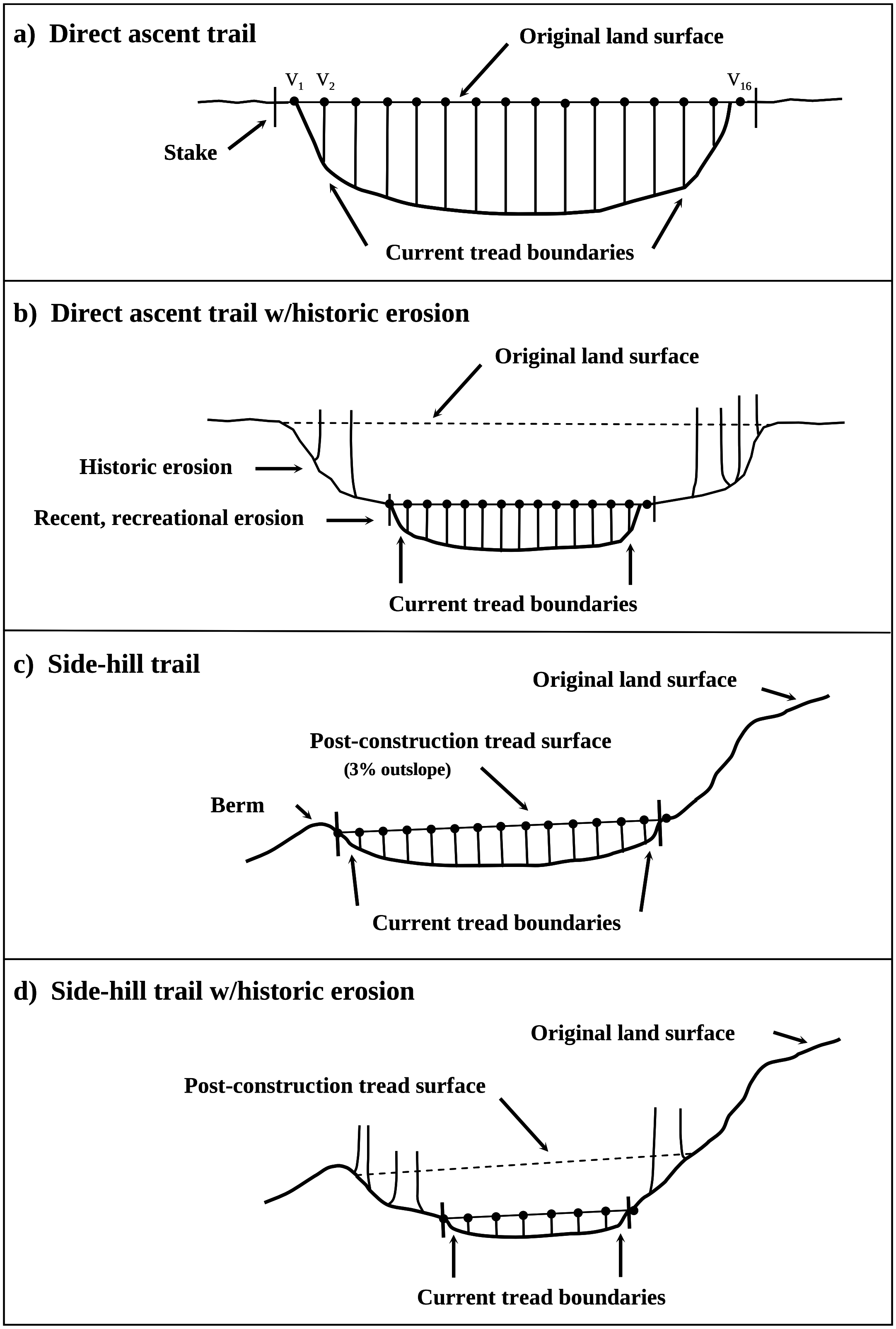


Figure 2. Cross sectional area (CSA) diagrams illustrating alternative measurement procedures for direct ascent trail alignments (a & b) vs. side-hill trail alignments (c & d) and for relatively recent erosion (a & c) vs. historic erosion (b & d).

Sample Cross Sectional Area Field Data Form

CSA		CSA		CSA	
Transect					
V_2=					
V_3=					

Transect code = 5 digit number

Point Sampling Form

Trail Segment ________ Surveyors ________________ Date ________

Transect	TG	LG	TSA	TX	ED	ST	TW	TLO	CSA	MI	Tread Substrate Characteristics
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											0 10 20 30 40 50 60 70 80 90

TG = Trail Grade **TSA = Alignment** **S = Soil** **G = Gravel**
LG = Landform Grade **ST = Secondary Treads** **TLO = Transect Line Offset** **L = Litter** **RT = Roots**
ED = Erosion/Deposition **TW = Tread Width** **CSA (calculated)** **V = Vegetation** **W = Water**
TX = Texture **MI = Max. Incision** **R = Rock** **WO = Wood, human-**
placed
M = Mud **O = Other (Specify)**