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The influence of use-related, environmental, and managerial factors on soil loss from recreational trails

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ABSTRACT

Recreational uses of unsurfaced trails inevitably result in their degradation, with the type and extent of resource impact influenced by factors such as soil texture, topography, climate, trail design and maintenance, and type and amount of use. Of particular concern, the loss of soil through erosion is generally considered a significant and irreversible form of trail impact. This research investigated the influence of several use-related, environmental, and managerial factors on soil loss on recreational trails and roads at Big South Fork National River and Recreation Area, a unit of the U.S. National Park Service. Regression modeling revealed that trail position, trail slope alignment angle, grade, water drainage, and type of use are significant determinants of soil loss. The introduction of individual and groups of variables into a series of regression models provides improved understanding and insights regarding the relative influence of these variables, informing the selection of more effective trail management actions. Study results suggest that trail erosion can be minimized by avoiding “fall-line” alignments, steep grades, and valley-bottom alignments near streams, installing and maintaining adequate densities of tread drainage features, applying gravel to harden treads, and reducing horse and all-terrain vehicle use or restricting them to more resistant routes.

This research also sought to develop a more efficient Variable Cross-Sectional Area method for assessing soil loss on trails. This method permitted incorporation of CSA measures in a representative sampling scheme applied to a large (24%) sample of the park’s 526 km trail system. The variety of soil loss measures derived from the Variable CSA method, including extrapolated trail-wide soil loss estimates, permit an objective quantification of soil erosion on recreational trails and roads. Such data support relational analyses to increase understanding of trail degradation, and long-term monitoring of the natural and recreational integrity of the trail system infrastructure.

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1. Introduction

Recreation-related impacts in protected natural areas are an increasing concern for land managers, who are generally guided by mandates requiring the preservation of natural conditions and provision of recreational opportunities (Hammitt and Cole, 1998; Leung and Marion, 2000). Impacts to flora, fauna, and water resources are generally most pronounced at locations receiving concentrated visitor use, including trails, campsites and various types of day-use recreation sites. Of these impacts, managers of National Park Service (NPS) backcountry areas identified trail impacts as the most widespread and challenging problem (Marion et al., 1993). Soil erosion was cited as the most widespread trail impact, with 44% of managers indicating it as a problem in “many or most areas” of their parks. Such challenges are likely to continue as trail-related recreational uses continue to expand, as suggested by the U.S. National Survey on Recreation and the Environment, which identified substantial increases in horseback riding (45%), bicycling (53%), hiking (183%) and backpacking (217%) from 1983 to 2000 (Cordell and Overdevest, 2001).

Common trail impacts include vegetation loss and compositional change, tread widening, muddiness, proliferation of informal (visitor-created) trails, and soil erosion (Hall and Kuss, 1989; Hill and Pickering, 2006; Marion and Leung, 2001). Furthermore, soil erosion from trails can degrade more distant natural systems, such as aquatic resources and organisms harmed by increased turbidity and sedimentation (Hammitt and Cole, 1998). Trail erosion, in particular, is a significant management concern because it is irreversible without costly management actions that may further impact resources or increase the

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development and artificiality of recreation settings. When substantial, trail erosion can degrade visitor experiences and create difficult or unsafe travel conditions (Leung and Marion, 1996; Marion and Leung, 2001). Park visitors have also demonstrated a low tolerance to erosion on hiking trails and near stream banks in protected natural areas (Noe et al., 1997).

Scientific understanding of factors influencing the trail erosion process can lead managers to the most effective means for designing and managing sustainable trail systems (Farrell and Marion, 2002; Leung and Marion, 1996; Newsome et al., 2002) (Table 1). While the action of water, and to a lesser extent, wind, feet, hooves, and tires, are the direct causal forces of erosion, other influential factors can be managed to minimize the loss of trail soils (Newsome et al., 2004; Summer, 1980). For example, understanding the specific nature of impacts resulting from different trail use types can guide managers in developing visitor and trail management practices to minimize erosion. Marion (1994) observed that the heavy ground pressure exerted by horse hooves accelerates erosion and muddiness on trails by removing vegetative and organic cover, compacting underlying soils to an impermeable hardpan, and churning or displacing surface soil particles making them more available for erosion or prone to muddiness.

Managers can limit contributing factors to erosion, such as trail alignments that allow topography to channel water along treads, while maintaining trails or managing visitors to provide safe and sustainable recreational opportunities. Comparisons of trampling and erosion indicators by use type has found horse use to be significantly more impacting than hiking, llama use, and mountain biking (Cole and Spildie, 1998; Dale and Weaver, 1974; Marion and Wimpey, 2007; Newsome et al., 2004; Thurston and Reader, 2001; Wilson and Seney, 1994). This is largely attributable to the heavy weight of horses and riders, exerting a ground pressure of approximately 43,590 kg-force/m^2 for shod horses, compared to 2039 kg-force/m^2 for a hiker wearing boots (Liddle, 1997). Motorized uses, including 2- and 4-wheel drive vehicles, all-terrain vehicles and motorcycles, have a greater potential for impact than non-motorized uses due to a number of factors (Liddle, 1997). Tires that spin at higher rates of speed cause more substantial abrasion damage to vegetation, roots and soils. Meyer (2001) observed that all-terrain vehicle (ATV) impacts from pressure-bearing tires can result in shearing and pumping actions that readily breakdown soil structure and lead to particle erosion. The greater weight and ground pressure of vehicles also cause greater soil compaction, shearing, and displacement – actions that cause soil rutting through the compaction or displacement of soil.

High quality information about trail and environmental conditions is critical for trail design, construction, and long-term maintenance. Trail managers and researchers, often faced with limited budgets and specific data needs, must choose from different information gathering methods and techniques that meet an appropriate balance between efficiency, data accuracy, and reliability. A review of methods by Hammitt and Cole (1998) found that the Cross-Sectional Area (CSA) method was the most accurate and reliable methodological approach, but that it was less efficient than others. However, alternate methods, such as simple maximum incision measures or categorical erosion ratings, are incapable of providing trail-wide estimates of soil loss. Refinement of the CSA method could increase efficiency and preserve data quality.

The primary objective of this exploratory research is to improve understanding of the relationships and relative influence of factors influencing Cross-Sectional Area soil loss to improve guidance for land management professionals responsible for managing sustainable trails systems. A secondary objective is to develop and apply a Variable Cross-Sectional Area method that more efficiently measures trail soil loss and explore its statistical utility in analyses seeking to understand factors that influence trail erosion. Study results include management implications of the regression analyses and the utility of the new trail erosion assessment procedure for trail condition assessment and monitoring.

2. Methods

2.1. Study area

The study area for this research was Big South Fork National River and Recreation Area (BSFNR), located in south-central Kentucky and north-central Tennessee, USA. This National Park Service (NPS) managed park encompasses 50,990 ha and receives nearly 900,000 visitors annually, with trail-related recreational activities accounting for a large portion of total visitor use. The BSFNR contains approximately 526 km of single and multi-use trails used primarily by horseback riders, though ATV use, hiking, and mountain biking are also common recreational activities.

Approximately one-half of the BSFNR is a river gorge featuring many sheer bluffs and deep narrow drainages that feed into the Big South Fork River – designated an Outstanding National Resource Waters area. Six mussel species are federally listed as endangered and are threatened by sedimentation in park waterways (National Park Service, 2003). Vegetation consists of river birch and sycamore in floodplains; hemlock in narrow gorges and along streams; beech,

Table 1
Attributes of environmental, managerial and use-related factors that contribute to greater susceptibility of trail soil erosion.

Factors	Attributes contributing to greater erosion susceptibility	Citations
Environmental		
Geology	Soils with homogeneous texture soils; fine- and coarse-grained soil textures	Bratton et al. (1979), Bryan (1977), Burde and Renfro (1986), Helgath (1975), Meyer (2002), Whinam and Comfort (1996)
Climate	High precipitation rates	
Topography	Steep landforms; high elevation; proximity to rivers and streams	
Vegetation	Mature forests; mesic forests; broad-leafed ground vegetation	
Managerial		
Trail design	Steep trail grades; trails aligned congruent with prevailing slopes; tread not outsloped; lack of grade reversals	Birchard and Proudman (2000), Cole (1989), Farrell and Marion (2002), Hesselbarth and Vachowski (2000), IMBA (2004)
Maintenance	Non-existent or ineffective tread drainage features	
Visitor-related	Failure to regulate type or amount of use; lack of low-impact behavior education	
Use-related		
Use amount	High use in sensitive vegetation and/or soil types	Cole (1983), Deluca et al. (1998), Farrell and Marion (2002), Leung and Marion (1999b), Sun and Liddle (1993)
Use type	Improper use type for environmental and design factors	
User behavior	Failure to stay on maintained path; high use during wet conditions	

sugar maple, and yellow birch-with oaks on the middle and lower slopes; mixed oaks and hickory in gently sloping upland areas; and Virginia pine on dry ridges and cliff-lines. Gorge soils are in the Ramsey–Hartells–Grimsely–Gilpin group complex, and plateau soils are in the Hartsells–Lonewood–Ramsey–Gilpin group complex. While richer in the floodplains, they are generally, thin, acidic, and sandy.

2.2. Sampling and measurement procedures

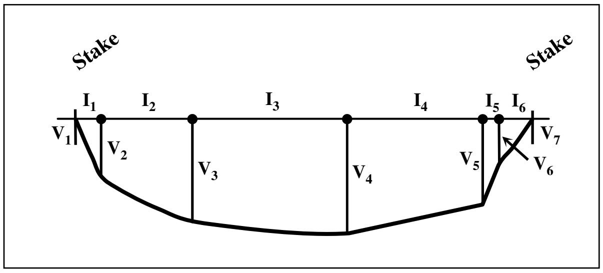
A use type stratified random sample, taken from the BSFNR Geographic Information System recreational trails and primitive roads database, was produced using the SPSS Random Sample procedure. The objective of the use type stratification was to match the proportion of trail mileage for use types in the sample to the proportion of trail mileage for use types in the population. Where necessary, trails were subdivided into 9.7 km segments to avoid under-sampling longer trails. Of the resulting trail population (526 km, 171 trail segments) a large (24%) sample was taken (126 km, 47 trail segments). This was to ensure an adequate quantitative representation of diverse environmental, managerial, and use-related factors for an accurate inventory of baseline conditions for the entire trail system (Cole, 1983). Amount of use (high, medium, low) and percentage use by mode of travel (horse, hike, mountain bike, ATV) were categorically assigned for each segment by a knowledgeable park trail manager. This individual has extensive observational knowledge of current and historical trail use patterns and his judgments provided the best available information. Segments receiving an estimate of 75% or more of any use type were categorized as representative of that type for use type analyses; remaining segments were categorized as "mixed use."

A point-sampling method using a systematic interval following a randomized start was used to locate transects along each trail where trail conditions were assessed (Farrell and Marion, 2002; Marion and Leung, 2001). An interval of 152 m was used following guidance provided by Leung and Marion (1999a). A measuring wheel (1.2 m circumference) was used to identify transect locations. At each sample point, a transect was established perpendicular to the trail tread with endpoints defined by visually pronounced changes in non-woody vegetation height (trampled vs. untrampled), cover, composition, or, when vegetation cover is minimal or absent, by disturbance to organic litter. The objective was to define the trail tread that receives the majority (>95%) of traffic, selecting the most visually obvious boundaries that can be most consistently identified. Temporary stakes were placed at these boundaries and the distance between was measured as tread width. The percentage of this width with visible human-placed gravel was also estimated to the nearest 5%.

The grade of the trail and the trail slope alignment angle, the difference in compass bearing between the prevailing landform slope (aspect) and the trail's alignment angle at the sample point, were assessed at each transect. A trail aligned along the contour would have a slope alignment angle of 90°, a trail aligned congruent to the landform slope would be 0°. Trail position relative to the local topography was determined as valley-bottom, mid-slope, or ridge-top. Soil texture at each transect was assigned to one of nine categories in the field following the method described by Foth (1990). Tread drainage was assessed with two measures. The distance in 7.6 m increments up to 22.9 m, to any reasonably effective human-constructed tread drainage feature (water bar or drainage dip) located in an upslope trail direction from the sample point was assessed to evaluate the efficacy of such features. Water drainage in the vicinity of sample points was also assessed as an estimate of the amount of water, in 25% categories, that would flow off the tread within 3 m in the upslope direction during an average rain event.

Soil loss at each transect was measured using a variable interval Cross-Sectional Area (CSA) method (Fig. 1). The Variable CSA method is an adaptation of the fixed interval method described by Cole (1983) designed to reduce measurement time without sacrificing accuracy. A taut nylon line was stretched between the trail boundary stakes from their base at the ground surface. To conserve time at minimally eroded locations the CSA procedure was applied only when maximum incision from the string to the tread surface exceeded 2.5 cm. At such locations CSA was assessed by taking vertical measurements along the horizontal transect line at points directly above tread surface locations where changes in tread micro-topography occurred (see Fig. 1). Sliding beads were positioned along the transect string to identify the locations for vertical measures, the number of which varied with tread surface complexity. The distance from each bead to the left boundary stake was recorded, along with the vertical measure of incision under each bead. Excel spreadsheet formulas were developed to calculate CSA based on these data. A field manual providing a detailed description of all procedures is contained in Marion and Olive (2006).

We note that use of a visitor trampling disturbance definition for establishing trail boundaries, from which CSA soil loss is assessed, will underestimate soil erosion from the time of trail creation. For example, a trail that is entrenched a meter deep has sides that are not traveled upon, so tread boundaries would be placed only as high as trampling disturbance was evident. This was viewed as valid as our intent was to assess erosion associated with relatively recent recreational use rather than "historic" erosion from earlier pre-park uses, or from soil excavation during trail construction. Trails with such historic erosion often followed old woods roads and nearly always had shrubs and trees rooted in the eroded embankments, indicating that the erosion had occurred more than 10–15 years ago. Finally, soil loss on minimally eroded treads with less than 2.5 cm incision was not assessed to conserve field assessment time. As a consequence, CSA measures were completed for 375 of the 821 transects in the sample population. While these procedures clearly underestimate soil erosion measures, we believe this is valid for two reasons: (1) underestimating recreation-related



Vertical (cm)	Interval (cm)	Area (cm^2)
V_1: 0	I_1: 5.0	21.3
V_2: 8.5	I_2: 12.5	146.9
V_3: 15.0	I_3: 20.0	360.0
V_4: 21.0	I_4: 16.5	272.3
V_5: 12.0	I_5: 2.5	21.9
V_6: 5.5	I_6: 5.0	13.8
V_7: 0	CSA:	836.0

Fig. 1. Illustration of the variable interval CSA method for assessing soil loss at each transect. Table shows data for use in the computational formula: area $= (V_i + V_{i+1}) \times I_i \times 0.5$ for each row and summed to compute CSA.

erosion is better than including soil loss caused by older pre-park trail or woods road uses or by trail construction work, and (2) focusing soil loss measures on more recent erosion is more managerially relevant for monitoring purposes and management decision making purposes.

2.3. Analyses

A series of multivariate regression analyses were run to examine the relative influence and relationships of numerous independent variables on the dependent Variable CSA. Coefficients of determination were compared between models to build a dynamic statistical representation of field conditions that allowed analyses of factors that influenced erosion. Influential variables were identified through forward and backward step-wise selection procedures in developing relational models of trail erosion. The focus of these analyses is on soil erosion because park staff and study findings revealed this form of trail degradation to be the most significant problem relating to the sustainability of park resources and trail-dependent recreational uses.

Categorical indicators (e.g., type of use) were analyzed by creating related sets of "dummy" variables. However, since regression procedures do not allow dummy variables to be included in complete sets, literature findings and managerial relevance were considered in producing two conceptual groupings of variables: (1) a baseline model of control variables, and (2) a set of main variables with a high degree of managerial relevancy and statistically significant effects on soil erosion. This separation was also done to statistically control for factors that have been shown in past literature to influence dependent variable values. Insignificant variables detracting from the relational model were excluded to avoid specification error.

2.3.1. Control variables

Baseline variables for the relational model take into consideration less influential variables that make significant contributions to CSA. Included variables are soil texture, water drainage, use level, and gravel percentage. Similar soil textures were aggregated to create the dummy variable categories loam, sandy loam, organic soil, and the reference category clay. Use levels are categorized as low, medium, and the reference category high.

2.3.2. Main variables

Four main independent variables were chosen on the basis of statistical significance, findings present in the literature, and managerial relevancy: trail position, trail slope alignment angle, use type, and trail grade. Trail position was categorized as ridge, mid-slope, and the reference category valley. Use type was categorized into hike, mountain bike, ATV, mixed, and the reference category horse.

2.3.3. Analysis methodology

Descriptive statistics were calculated to characterize the trail sample for all variables included in the analyses. Weighted least-squares regression analyses were used to examine the relationships and interactions of influential variables on soil erosion (CSA). One-way analysis of variance (ANOVA) tests were used within regression procedures to test for significant differences in effects on CSA. Dummy variable categories were tested with ANOVA relative to reference (omitted) categories. Finally, product terms were computed and tested using ANOVA for interactions between trail grade and slope alignment angle, and slope alignment angle and use type. Means for these variables were centered in the process to avoid multicollinearity.

Preliminary analyses revealed severe skew in the dependent variable, caused by a large number of zero values, where CSA was assumed to be zero because maximum incision was less than 2.5 cm. Also, a fanned pattern in distribution of standardized residuals revealed heteroskedasticity, which was found to be a function of extreme outliers and the distance of sample points to trailheads: as points increased in distance from trailheads, a pattern of irregularity in errors was observed.

To address these issues CSA was recoded as a binary response, where only values greater than zero ($N = 375$) were included in relational analyses. This was appropriate because the zero values did not undergo the CSA measurement procedure, and the distribution of CSA error values is assumed to be normally distributed in OLS regression. A weighted least-squares procedure was included in analyses to control the effects of distance, and six extreme high-end outliers were excluded ($N = 369$) to meet the assumption of homoskedasticity and provide an unbiased regression line fit. In addition, Tobit top and bottom end censuring regression using the statistical program Stata 8.3 was applied for comparison to the full sample base ($N = 821$) to address concerns that binary results would be biased due to the exclusion of zero measure "success" cases. By using the binary sample, interactions between main variables were studied from the computation of relevant product terms. The variance inflation factor (VIF) and a correlations matrix were examined for each variable in regression modeling to detect any unacceptable levels of multicollinearity. Neither cut-off points of 4 (VIF) and 0.75 (correlations) were violated, indicating that multicollinearity was not a problem.

Finally, to summarize the magnitude of use type contrasts, CSA values were extrapolated from each trail transect to the trail 76 m before and after the transect location to provide an estimate of total soil loss for each trail segment in cubic meters. Corrected calculations were required for the initial and final trail transects as their intervals were less than the standard 152 m.

3. Results

3.1. Multivariate results

Results from a series of regression analyses indicate the individual (Table 2) and collective (Table 3) contribution of each main effect variable to CSA, as terms are added into the statistically controlled regression model. This exploratory approach reveals how well-known factors quantitatively contribute in relative degrees to explain the variation in CSA values. In both tables, adjusted coefficients of multiple determination (R^2) represent the proportion of explained variation in CSA by the included independent variables. Table 2 presents five regression models that show the individual effects as each main variable is added. After the variability explained by the control set is removed (Model 1; $R^2 = 0.10$), the main variables are added individually in order of greatest to least variation explained. Trail topographic position explains the most variation in CSA (11%), showing that when compared to trails in the river valley, mid-slope and ridge-top positioned trails have significantly less soil loss (-755 cm^2 and -1032 cm^2, respectively; $p < 0.01$). Note that the valley position served as the "reference" category for this dummy coded variable, and has, by definition, a coefficient of 0.

Following trail position, trail alignment and use type each explain an additional 4% of CSA variance (Table 2). Trail alignment is a highly significant factor ($p < 0.01$), revealing that as trail slope alignments shift from orientations parallel to landform slopes (0°) to alignments along the contour (90°), that CSA values decline an estimated 8 cm^2 per degree of increase. The use type variable showed significant differences between hiking and horse riding uses, with substantially less erosion (-697 cm^2; $p < 0.01$) on hiking trails. Interestingly, trail grade, frequently cited as an influential factor for trail erosion, did not explain any additional variation in

Table 2
Effects of control and main variables across models on Cross-Sectional Area soil loss.

Variables	Regression models[a]				
	(1)	(2)	(3)	(4)	(5)
Control variables					
Soil texture					
Clay[b]	0	0	0	0	0
Sandy loam	−329 (0.047)[c]	−394 (0.012)	−303 (0.063)	−387 (0.020)	−258 (0.126)
Loam, silt loam	−123 (0.445)	−323 (0.049)	−58 (0.744)	−97 (0.586)	−90 (0.602)
Organic soil	−858 (0.021)	−800 (0.024)	−832 (0.024)	−581 (0.110)	−832 (0.028)
Use level					
High[b]	0	0	0	0	0
Medium	407 (0.024)	323 (0.050)	400 (0.021)	613 (0.008)	432 (0.015)
Low	−297 (0.538)	−58 (0.904)	−452 (0.348)	219 (0.787)	−335 (0.498)
Water drainage	−13 (0.000)	−13 (0.000)	−13 (0.001)	−13 (0.000)	−13 (0.060)
Gravel	−0.6 (0.816)	3 (0.362)	−0.6 (0.781)	−5 (0.130)	−1 (0.670)
Main variables					
Trail position					
Valley[b]		0			
Mid-slope		−755 (0.000)			
Ridge		−1032 (0.000)			
Trail alignment			−8 (0.000)		
Use type					
Horse[b]				0	
ATV				−484 (0.184)	
Hike				−697 (0.000)	
Bike				−942 (0.333)	
Mixed				−594 (0.000)	
Trail grade					13 (0.060)
Constant	1497	2194	1419	1742	1439
Adjusted R^2	0.10	0.21	0.14	0.14	0.10

[a] Unstandardized CSA coefficients, cm^2.
[b] Reference category for dummy coded categorical variables.
[c] Two-tailed *t*-test significance.

CSA when included with the control variables (Table 2). Post hoc testing revealed that the addition of control variables water drainage and soil texture diminishes the influence of trail grade. Results from these regression models aided in selecting contrasting relationships between factors chosen for the models presented in Table 3.

Interrelationships between individual factors are revealed in Table 3, and provide an improved understanding of how various assemblages of variables influence erosion. In general, the main variable effects are robust across models, though trail grade becomes a significant factor ($p < 0.01$) in Models 1, 3, and 4. Although statistically significant, trail grade only explains an additional 2% of CSA variation. However, a pronounced change occurs in the influence of use types when trail grade and trail position are also included (Models 3 and 4). These models associate ATV use with substantially higher levels of erosion than horse riding, in contrast to the lower predicted erosion in Table 2, Model 4. Furthermore, with inclusion of all main variables in Model 4 (Table 3), the predicted difference in erosion between hiking and horse use increases from 697 (Table 2, Model 4) to 916 cm^2, with hiking trails exhibiting significantly lower soil loss. The fully specified Model 4 has a total explained variance of 32%. The effects of both trail alignment and trail grade on CSA remain statistically significant ($p < 0.01$). The final model predicts that soil loss will increase 6 cm^2 for every degree trail slope alignment deviates from the contour, and 23 cm^2 for every percent increase in trail grade.

3.2. *Interaction effects*

Post hoc analyses applied to investigate potential interaction effects between trail grade and trail slope alignment angle revealed no interaction between product terms. Low values of slope alignment were correlated with higher values of trail grade, though it is not uncommon for trails with low grades to also have low slope alignments. Visual examination of a curve estimation suggested that slope alignment angle was a driving influence on CSA soil loss that was mediated by trail grade.

A similar post hoc analysis found a significant interaction effect ($p < 0.01$) between trail slope alignment angle and use type, but only horse use effects persisted across models with other control and main variables. The interaction effect of slope alignment angle on horse trails was revealed strongly as -14 cm^2 ($p < 0.01$) per degree at the centered mean of slope alignment angle (47°), but were not found with other use types. Use type contrasts (Table 4) provided by computation of new slope alignment angle values at one standard deviation above (74°) and below (20°) the centered mean provided a revealing perspective of the level at which trail slope alignment interacts with use type. When slope alignment was at one standard deviation above the mean, contrasts were strong only between horse and hiker use ($p = 0.07$), though not significant. At mean slope alignment, the magnitude of difference increased significantly for the hiker and mixed use categories. At one standard deviation below the mean, the interaction between horse use and other types strengthened substantially, with significantly greater effects from horse use than from hike (-1148, $p < 0.01$), bike (-1658, $p < 0.05$), and mixed (-594, $p < 0.01$) use types. These findings indicate that multiplicative effects of trail slope alignment can be expected with horse use at high levels of slope alignment in relation to hiking use, and as slope alignment angle decreases, differences are more pronounced with other uses. Stated more meaningfully, horses cause significantly greater erosion on trails aligned parallel to the landform slope than do hiking, biking, and mixed uses. Furthermore, *p* values indicated no significant difference between the magnitude of horse impacts and ATV impact

Table 3
Relational effects of control and main variables on Cross-Sectional Area soil loss.

Variables	Regression models[a]			
	(1)	(2)	(3)	(4)
Control variables				
Soil texture				
Clay[b]	0	0	0	0
Sandy loam	−303 (0.054)[c]	−323 (0.034)	−297 (0.058)	−323 (0.034)
Loam, silt loam	−290 (0.079)	−245 (0.134)	−142 (0.396)	−90 (0.573)
Organic soil	−755 (0.031)	−748 (0.030)	−626 (0.069)	−587 (0.080)
Use level				
High[b]	0	0	0	0
Medium	374 (0.024)	348 (0.029)	194 (0.361)	213 (0.024)
Low	−90 (0.864)	−206 (0.639)	439 (0.505)	323 (0.538)
Water drainage	−13 (0.000)	−6 (0.004)	−6 (0.009)	−5 (0.000)
Gravel	2 (0.542)	2 (0.465)	−3 (0.372)	−3 (0.816)
Main variables				
Trail position				
Valley[b]	0	0	0	0
Mid-slope	−877 (0.000)	−865 (0.000)	−1026 (0.000)	−1019 (0.000)
Ridge	−1071 (0.000)	−1052 (0.000)	−1032 (0.000)	−1006 (0.000)
Trail alignment		−6 (0.000)		−6 (0.000)
Use type				
Horse[b]			0	0
ATV			432 (0.218)	368 (0.279)
Hike			−903 (0.000)	−916 (0.000)
Bike			−929 (0.303)	−987 (0.262)
Mixed			−355 (0.033)	−432 (0.008)
Trail grade	19 (0.002)	13 (0.084)	32 (0.000)	23 (0.001)
Constant	2200	2135	2355	2329
Adjusted R^2	0.234	0.265	0.287	0.323

[a] Unstandardized CSA coefficients, cm^2.
[b] Reference category for dummy coded categorical variables.
[c] Two-tailed t-test significance.

contrasts, which suggested that ATVs also cause greater erosion on such “fall-line” trails than do hikers or bikers.

3.3. Magnitude of use type effects

The influence of use type on soil loss is further examined in Table 5, which presents a variety of CSA measures for each type of use. Testing of mean CSA values reveals that trails for which the predominant use is hiking (121 cm^2) are not significantly different from mountain biking trails (37 cm^2). These use types were significantly different from horse (965 cm^2) and mixed use (928 cm^2) trails, which were significantly different from ATV trails (1584 cm^2). CSA measures from trail sample points were also extrapolated to each full trail segment to estimate total soil loss. The total estimated amount of soil loss in the sample was 8309 m^3. The magnitude of type of use effects was clearly seen between horse and hiker uses, which had revealed significant differences ($p < 0.01$) consistently across the multivariate models.

The CSA m^3/km provides a standardized measure, as does the percentage of the total soil loss from the sample (Table 5). Soil loss on horse trails was estimated at 94.9 m^3/km, approximately eight times more than occurs on hiker trails (11.8 m^3/km). In contrast, mountain biking, at 3.5 m^3/km, has the lowest estimated level of soil loss, about 30% as much as on hiking trails. This finding reflects a limited mileage of trails where mountain biking was the predominant use (3.1 km), and these trails received low to moderate levels of use. While ATV trails had an estimated 143.9 m^3 of soil loss per km, the highest of any category, recall that difference was only significantly higher than horse use when use level was not considered. As a percentage of aggregate erosion, erosion from horse trails (50.5%) accounts for the majority of soil loss. Mixed use trails, for which the predominant use is horse riding, account for 35.5% of aggregate soil loss, followed by ATVs (8.0%), hikers (5.9%) and mountain bikes (0.1%).

Table 4
Use type contrasts across levels of trail alignment.

	Use type contrasts for trail alignment[a]		
	1 s above (x) 74°	Mean (x) 47°	1 s below (x) 20°
Use type			
Horse[b]	0	0	0
Hike	−406 (0.072)[c]	−781 (0.000)	−1148 (0.000)
ATV	600 (0.135)	271 (0.339)	−65 (0.880)
Bike	−665 (0.441)	−1161 (0.074)	−1658 (0.028)
Mixed	−45 (0.835)	−316 (0.027)	−594 (0.002)

[a] Unstandardized CSA coefficients, cm^2.
[b] Reference category for dummy coded categorical variables.
[c] Two-tailed t-test significance.

4. Discussion

This research developed and applied a point-sampling method for assessing trail conditions on a large (126 km) randomly selected sample of the BSFNR trail system (526 km). The sample was representative of the park’s various types and amounts of uses, topographic positions, soil types, and levels of trail design and maintenance. The new Variable CSA method provided an efficient procedure for assessing soil loss along trails and communicating results in a variety of meaningful measures. In comparison to previous studies employing more complex and time-consuming CSA variations (Burde and Renfro, 1986; Tinsley and Fish, 1985;

Table 5
Mean and estimated total CSA soil loss by use type.

CSA	Use type					
	Horse	Hiker	Bike	ATV	Mixed	All types
Mean (cm^2)[a]	965 ± 146^2	121 ± 44^1	37 ± 40^1	1584 ± 743^3	928 ± 253^2	673 ± 92
m^3/km	94.9	11.8	3.5	143.9	90.2	65.8
Sum (m^3)	4194	492	11	662	2950	8309
Total sum (%)	50.5	5.9	0.1	8.0	35.5	100

Superscript numerals refer to results from the LSD multiple comparison test for differences between means. Mean values with the same numeral are not significantly different ($p < 0.05$).

[a] Mean values with 95% confidence intervals. ANOVA: $F = 23.8$, $p < 0.01$.

Yoda and Watanabe, 2000), the Variable CSA method permitted the efficient measurement of soil loss using a point-sampling method employing fixed-intervals and a random start so that representative data could be collected. The large dataset permitted the extensive use of regression modeling to investigate the type and extent of influence by use-related, environmental and managerial factors. The representative sampling schemes employed for selecting trail segments and transects also permitted the extrapolation of CSA soil loss measures to volume estimates of aggregate soil loss for trail segments, the sample, and the entire BSFNR trail system. Various standardized measures (mean, m^3/km, %) can also be derived for making objective comparisons of soil loss across use types, trails, or protected areas.

Study findings reveal a trail system with substantial soil erosion problems, with estimated soil loss of 8309 m^3 for the sample and 34,687 m^3 for the entire trail system. For perspective, these amounts equate to about 1093 and 4564 single-axel dump trucks (7.6 m^3 capacity) of soil for the sample and trail system, respectively. These are considered conservative estimates of soil loss as procedures omitted CSA measures on transects with <2.5 cm of incision and sought to exclude erosion from historic trail/road uses and trail construction. This substantial loss of soil is considered an essentially irreversible form of recreational impact as the soil cannot be returned or easily replaced. This level of soil loss also has high ecological significance due to its potential to threaten water quality (Fig. 2), and high social/human significance due to increased hiking difficulty and threats to visitor safety and the aesthetic quality of the park's trail resources. The authors are aware of no other studies that have extrapolated representative soil loss estimates to a park-wide trail system so comparisons to other protected natural areas are not possible.

Fig. 2. Soil loss from this heavily used horse trail drains directly into a small stream. Field staff noted this was a common occurrence.

4.1. Use-related variables

Multivariate regression analysis modeling was directed at improving understanding of the relative influence of and relationships between various use-related, environmental and managerial variables. Results of this research include important implications for trail management, particularly in the design, maintenance, and type of use designations. Type of use was found to be a substantially greater determinant of trail degradation than amount of use. As shown in the fully specified regression model (Table 3, Model 4), the range of values for CSA coefficients across use levels is much lower than for type of use and several other variables. Furthermore, the substantial influence of these other variables in the model has so altered the "apparent" influence of use level that the resulting coefficients suggest that high use trails have the least erosion. The coefficients for influential and statistically significant variables can be meaningfully interpreted in multivariate analyses; coefficients for less influential variables are frequently meaningless. Further, this finding is consistent with other studies that have reported amount of use to be a poor predictor of soil loss on trails (Cole, 1983; Dale and Weaver, 1974; Dixon et al., 2004; Farrell and Marion, 2002).

In comparison, the wide range in coefficients for type of use, along with their significance, suggests that managers would be far more successful in limiting soil loss by focusing management attention on trail type of use designations. These regression models and the extrapolated aggregate soil loss estimates presented in Table 5 reveal that ATV and horse use are significantly greater contributors to soil loss than are hiking and mountain biking uses. These data are not presented to apportion blame to specific use types, rather to emphasize that managers seeking to accommodate horse and ATV uses should acknowledge their higher potential for eroding soil and incorporate improved trail design, construction, maintenance and visitor use management practices to ensure that the impacts of such uses are minimal and acceptable.

Additional research on ATV effects is needed to verify these findings. One limitation of this study is that ATV use is more recent than horse and hiker use at BSFNR, and may simply be occurring on trails and roads that were already substantially eroded. Additional empirical studies in areas with extensive ATV trail systems and experimental design studies are needed to extend knowledge of ATV impacts and their management. Given the rapid growth in this use type such research is critical to the development of best management practices. At BSFNR, trails are not currently designated or maintained for ATV use and field staff noted widespread illegal use on non-motorized trails. Given the greater speed and range of these vehicles, and their substantial potential for eroding soil due to engine torque and knobby tires, managers of protected natural areas should be cautious in allowing their use until sustainable trail alignments are identified, developed and hardened, and adequate maintenance, monitoring, and visitor management programs are implemented to ensure unacceptable resource impacts do not occur.

4.2. Environmental variables

Among environmental attributes, trail position was the strongest and most robust determinant of soil loss across models. Valley positions were significantly more eroded than mid-slope and ridge trails. However, this result is likely influenced by a combination of periodic flooding-related erosion of trail substrates and of being in a lower watershed position where water runoff volumes and rates are highest. Some implications of these results are that: (1) trail placement in floodplains should be avoided, (2) valley positioned trails should be located above frequent flood-levels and designed with side-hill alignments that can be easily drained, and (3) more erosive types of uses (e.g., horse and ATV use) should be restricted from riparian area trails where possible.

Trail alignment to the landform slope as a determinant of soil loss was also identified as a major and robust influence. This variable has been rarely mentioned in the research and trail maintenance literature (see Leung and Marion, 1996) yet this research revealed it to be a better determinant of soil loss than trail grade (compare Models 1 & 2, Table 3). Trails routed across slopes (closer to the contour) have significantly less soil loss because the terrain on one side of the trail is always lower, allowing easier tread drainage by outsloped treads, water bars, drainage dips or grade reversals. In contrast, it is often impossible to remove water from the incised treads of "fall-line" trails aligned with landform slopes. Many existing formal and informal trails are aligned with landform slopes because little or no tread construction was needed to create the trail; many were simply "walked in" by trail users. These results indicate that while construction costs are greater for side-hill (bench-constructed) trails, such alignments are inherently more sustainable – facilitating water drainage and suffering less erosion over time when properly maintained. The most sustainable trails employ side-hill designs with periodic grade reversals to remove flowing water; reliance on tread outsloping, water bars, or drainage dips to remove water require continual maintenance to maintain their efficacy (Birchard and Proudman, 2000; Marion and Leung, 2004).

The multiplicative interaction effect of slope alignment angle with horse use reveals the need to maintain a consistently high alignment angle (e.g., $>48°$) for trails receiving horse use, as it more than doubles the additive alignment effects on trail erosion. Horse trails with segment slope alignments at 47° or less should be monitored closely, frequently maintained, and relocated or re-designated for another use if erosion cannot be abated. Based on the ATV coefficients in Table 4 these same findings and implications also apply to ATV trails.

Other studies and trail maintenance books have long emphasized, but rarely quantified, the influence of trail grade on soil erosion (Birkby, 1996; Bratton et al., 1979; Hesselbarth and Vachowski, 2000; Tinsley and Fish, 1985). As determined by the best regression model, CSA increases 23 cm^2 for every 1% increase in trail grade (Table 3, Model 4). This estimate is an approximation of the influence of grade that incorrectly suggests a linear relationship. Research on forest roads show that erosion rates increase with increasing slope, rising exponentially at the highest grades (Dissmeyer and Foster, 1984; Liddle, 1997).

Regression modeling and post hoc testing revealed trail grade to have some complex interrelationships with other variables. For example, results show that water drainage and soil texture diminished the effect of trail grade. Trails can have steeper grades without suffering significant erosion if tread soils have heterogeneous textures, such as loams, particularly when substantial amounts of rock are also present (Bryan, 1977; Welch and Churchill, 1986). Adequate densities of functional tread drainage features must also be present. While Post Hoc testing found no significant interaction between trail grade and slope alignment angle these variables are correlated: "fall-line" trails often have steeper grades. The addition of use type to the regression model strengthened the influence of trail grade (compare models 1 and 3, Table 3); possibly the inclusion of trail grade accounts for higher erosion rates on steeper horse and ATV trails. The influence of trail grade is retained (though diminished) even with the addition of trail slope alignment angle (compare models 3 and 4, Table 3); fall-line trails in flatter terrain have limited erosion potential in contrast to fall-line trails in steep terrain. These empirical data support an earlier speculation by Leung and Marion (1996): "the importance of slope alignment angle increases in its significance as trail grade increases."

All regression models found clay soil textures to have greater soil loss than the other soil types, particularly in comparison to sandy loam and organic soils (Tables 2 and 3). Clay is a homogeneous-textured soil, which is more prone to erosion than soils with a wide range of particle sizes, such as loams (Hammitt and Cole, 1998; Liddle, 1997). Clay soils also compact tightly and cause greater runoff than other soil textures. Organic soils are quickly eroded from most trail treads, except in flatter terrain and depositional environments that receive eroded soils.

4.3. Managerial variables

Managers do have control over attributes addressed under environmental variables (e.g., trail slope alignment angle and grade), but only when designing new trails or relocating segments of existing trails. On pre-existing trails, managers have greater control over attributes such as tread drainage and applying gravel to reduce erosion. Water drainage remained a highly significant determinant of soil loss in all but one regression model, indicating the importance of this management variable. One reason contributing to the significant amount of soil loss on BSFNR trails was the relative paucity of tread drainage features. For example, drainage of water from the trail within 3 m in an up-hill trail direction was rated as 0% for 51% of the sample points. The presence and distance to human-constructed tread drainage features (water bars or drainage dips) were also assessed in an up-hill direction from each sample point (see Section 2). These data were unusable in regression equations because only 59 drainage features were found; 768 (93%) of the sample points had no drainage feature placed within 30.5 m. Regardless, an analysis of CSA soil loss by proximity to drainage features was statistically significant (ANOVA $F = 4.2$, $p < 0.05$), with mean CSA of 361 cm^2 for sample points with a drainage feature within 7.6 m in an up-hill direction, 1013 cm^2 for points with a feature within 7.7–15.2 m, and 1626 cm^2 for points with a feature within 15.3–22.9 m. Clearly these features are highly effective if placed in sufficient density (which varies with trail grade) and periodically cleaned to maintain their effectiveness.

Gravel application was not a significant determinant of soil loss in any of the regression equations. This result is likely due to the relative rarity of gravel application; only 36 of the 369 sample points (10%) included in these analyses had gravel coverage of 50% or more. This unexpected finding was investigated further in the study's research report after selecting only cases where gravel cover was present ($N = 162$) (Marion and Olive, 2006). Trail grade was included in the analysis to examine the extent to which gravel limits soil loss with increasing grade. Fig. 3 illustrates the results of an ANOVA test (General Linear Model) that revealed the model and both indicators to be highly significant ($F\,(\text{model}) = 6.2$, $p < 0.01$; $F\,(\text{gravel}) = 9.9$, $p < 0.01$; $F\,(\text{grade}) = 13.3$, $p < 0.01$) with an insignificant interaction term. Trails with little or no visible gravel cover

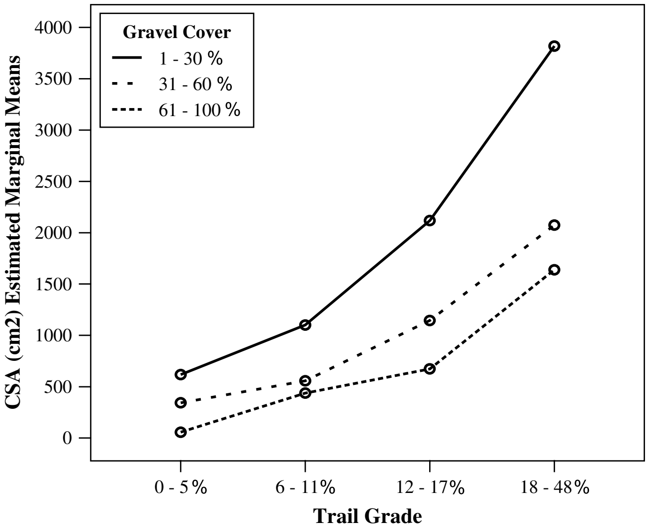


Fig. 3. The influence of gravel application and trail grade on CSA soil loss (source: Marion and Olive, 2006).

have significantly greater erosion, particularly at grades above 11%. Graveling is most effective on trails with grades less than 12%, particularly for trails with 61–100% gravel coverage. Another important implication is that well-graveled trails reduced soil loss on the steepest trails (18–48%) by approximately 75% (Fig. 3).

4.4. *Research needs*

Additional research is needed to investigate methods for standardizing assessments of soil loss when permanent transects are not employed. This is particularly critical when the objective of soil loss measures is to monitor change over time. Differences in judgments for establishing transect lines are likely to be more consistent within surveys than between surveys. Improved diagrams, more detailed procedures, and photos are needed to minimize subjectivity involved with fixing transect endpoints and height. Investigations of the accuracy, precision and efficiency of alternative CSA procedures are also needed. For example, does the small gain in efficiency associated with the Variable CSA method come at a cost in accuracy or precision?

Inclusion of the trail slope alignment indicator is recommended in future studies investigating soil loss on recreational trails and roads. Its relationship to trail grade and other variables requires further examination across the entire range of slope alignment angles. Some significant relationships revealed in this study also provide a basis for future experimental designs seeking to investigate the complex interplay between influential factors of soil loss. While this study demonstrated the importance of trail slope alignment angle, its results provide only general guidance in determining the point at which alignment angles become unacceptably low. Furthermore, how does guidance to avoid low trail slope alignment angles (e.g., less than 20°), compare to other guidance such as the “Half Rule” proposed by the International Mountain Biking Association (IMBA, 2004)? This rule states that trail grade should never exceed half of the landform grade to keep water from diverting down the tread.

The substantial and continuing increases in mountain biking and ATV riding require additional research attention to understand the unique impacts associated with these relatively new activities. Such research can provide new knowledge to develop best management practices for the design, construction, and maintenance of trails able to sustain these uses with minimal resource impacts.

It is also useful to consider why the best regression model (Table 3, model 4) explains only 32% of the variation in CSA. While we sought to accurately measure and incorporate a variety of relevant environmental, use-related, and managerial variables into the regression analyses it is helpful to speculate on what future studies might do to increase their explanatory power. In our judgment, potentially significant variables not accounted for are the related factors of trail age and amount and efficacy of trail maintenance work. For example, a poorly designed trail that is relatively new or that has been consistently well-maintained would not show substantial soil loss, while a well-designed trail that is old and/or has not been maintained over time might show substantial erosion. Improved measurements of factors included in this study could also help, particularly in assessing the amount of use and changes in amount or type of use over time. Applications of experimental designs capable of evaluating the relative influence of a variety of influential variables are likely to have greater success, though the large number of variables that require evaluation present significant changes to this approach as well.

Finally, research on the fate of eroded soil from trails is also needed, particularly in riparian environments. How much of the soil eroded from trails reaches water bodies and what is the nature, extent and ecological significance of its impact to aquatic organisms?

5. Conclusion

A trail system, that facilitates access to remote destinations, provides safe, high quality recreational experiences, and concentrates traffic on durable treads maintained to minimize resource degradation can only result from professional planning and management. This research sought to inform such management by investigating the influence of use-related, environmental and managerial factors on soil loss on recreational trails and roads at BSFNR. Substantial tread erosion was documented on trails where horse and ATV uses are predominant while hiking and mountain biking trails are generally in good condition. The potential transport of eroded soils into park waterways and the potential for negative sedimentation and turbidity impacts to federally listed endangered mussels, trout populations, and other aquatic organisms are critical management concerns.

A complex interplay of factors, both casual and non-causal, has been suggested by previous research as influencing soil erosion on trails. Regression modeling of environmental, managerial, and use-related influences revealed that trail position, trail slope alignment angle, grade, water drainage, and type of use are all significantly influential variables in the best trail soil loss model. Improved understanding and insights regarding the relative influence of these variables permits the selection of more effective trail management actions, and can be used to justify difficult decisions or to garner staffing and funding support within land management agencies. For example, these study results suggest that trail erosion can be minimized by avoiding “fall-line” alignments, steep grades, and valley-bottom alignments near streams, by installing and maintaining adequate densities of tread drainage features, applying gravel to harden treads, and by reducing horse and ATV use or restricting them to more resistant routes. Surveys of existing trail alignments can identify segments or trails requiring reroutes with improved alignments. It is important to recognize that some trail segments cannot be maintained to prevent resource degradation and that substantial one-time investment in realignments will be more than compensated by avoiding substantial soil loss and long-term savings in repeated, and often unsuccessful, maintenance work.

A secondary objective of this research was the development and application of a more efficient Variable CSA method for assessing soil loss. Though additional research is needed to evaluate its accuracy, precision and efficiency, the Variable CSA method permitted incorporation of CSA measures in a representative sampling scheme that included 821 trail transects. The efficiency of collecting soil loss data over such a large sample was increased by omitting CSA measures at minimally eroded transects (incision < 2.5 cm), reducing the number of assessed transects to 375. The variety of soil loss measures derived from the Variable CSA method, including extrapolated trail-wide soil loss estimates, permit an objective quantification of soil erosion on recreational trails and roads. Such data support relational analyses, as presented in this paper, to increase understanding of trail degradation and the relative importance of causal and influential factors.

The Variable CSA method also efficiently yields data applicable to the long-term monitoring of trail erosion and contributes to an improved understanding and communication of trail infrastructure condition. This is particularly important, as backcountry trails are often “out of sight and mind” for policy makers. Incorporation of trail condition indicators into carrying capacity planning and management decision making frameworks such as the Visitor Experience and Resource Protection (VERP) and Limits of Acceptable Change (LAC) can ensure that land managers monitor trail conditions for comparison to standards of quality. VERP and LAC require implementation of corrective actions when standards are violated, assisting managers in meeting legislative mandates by maintaining the natural and recreational integrity of their trail system infrastructure. As popular demand for trail experiences increases and funds for the proper design, construction, and maintenance of trail resources remain in competition with other management budgetary needs, it is increasingly important to provide an objective and effective voice for trail conditions.

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