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Research article

Assessing the influence of sustainable trail design and maintenance on soil loss

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ABSTRACT

Natural-surfaced trail systems are an important infrastructure component providing a means for accessing remote protected natural area destinations. The condition and usability of trails is a critical concern of land managers charged with providing recreational access while preserving natural conditions, and to visitors seeking high quality recreational opportunities and experiences. While an adequate number of trail management publications provide prescriptive guidance for designing, constructing, and maintaining natural-surfaced trails, surprisingly little research has been directed at providing a scientific basis for this guidance. Results from a review of the literature and three scientific studies are presented to model and clarify the influence of factors that substantially influence trail soil loss and that can be manipulated by trail professionals to sustain high traffic while minimizing soil loss over time. Key factors include trail grade, slope alignment angle, tread drainage features, and the amount of rock in tread substrates. A new Trail Sustainability Rating is developed and offered as a tool for evaluating or improving the sustainability of existing or new trails.

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1. Introduction

Achieving conservation objectives in protected natural areas requires the ability to sustain visitation while avoiding or minimizing adverse environmental impacts. While roads provide visitor access to protected natural areas, trails are often the predominant means of access within protected areas. Some trails, such as the Appalachian National Scenic Trail in the U.S., the Via Alpina and Grand Randonnée 20 trails in Europe, and the Overland Track in Australia, are themselves a primary attraction feature that draws visitation to protected natural areas. Trails are an essential infrastructure component that can minimize resource impacts by concentrating traffic on hardened treads sustainably designed and maintained to limit the areal extent and severity of resource impact. In this paper we define a sustainably designed trail as one that limits both trail degradation and annual maintenance while accommodating its intended amount and type of use.

Concentrated traffic from hikers, backpackers, mountain bikers, and horse riders on natural surfaced trails removes or prevents the establishment of vegetative and organic litter cover on treads, compacts substrates, and increases water runoff and the erosion of soil (Hammitt et al., 2015; Marion et al., 2016; Whinam and Chilcott, 2003; Wilson and Seney, 1994). Trails in flat terrain can also suffer from trail widening, braiding, and muddiness (Leung and Marion, 1996; Wimpey and Marion, 2010). From a conservation perspective, the loss of soil is perhaps the most significant form of environmental impact because it is long-term or irreversible without substantial management action, and eroded soil can enter waterways, causing secondary impacts to aquatic environments (Marion et al., 2016; Olive and Marion, 2009). The rutting, exposed roots and rocks, and tread roughness caused by soil loss also: 1) increases the difficulty of hiking or riding, 2) diminishes aesthetic qualities, 3) impedes maintenance efforts to remove water from incised treads, and 4) contributes to trail widening, expanding the total area of disturbance associated with trail networks, (Marion et al., 2016). While some of these environmental impacts are unavoidable, excessive impacts threaten resource protection values, visitor safety, and the quality of recreational experiences.

Trail degradation, particularly soil loss, is a complex process. Soil scientists have developed a number of soil erosion models for agricultural settings, beginning with the universal soil loss equation (USLE) and later improved as the RUSLE (Kirkby, 1980; Renard et al., 1997). The models predict average annual soil loss based on six factors, including soil erodibility, rainfall erosivity, topography

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(slope length and steepness), cover management, and support practice. These models and others (e.g., the Water Erosion Prediction Project for forest roads, WEPP_Road) have been adapted and applied to forest roads (Croke and Nethery, 2006; Rhee et al., 2004; Wade et al., 2012), and even to unsurfaced trails (Aust et al., 2004; Kidd et al., 2014). However, these models have not been validated for trails, which have substantially different watersheds and uses than agricultural settings and forest roads.

Recreation ecology studies have also investigated numerous factors that influence trail soil loss, including use-related factors such as the amount, type, and behavior of trail users, environmental factors such as soil and vegetation abundance and type, and managerial factors such as trail design, construction, maintenance, and visitor use regulation and education programs (Leung and Marion, 1996, 2000; Newsome et al., 2001; Olive and Marion, 2009; Ramos-Scharrón et al., 2014). Much of the existing research has focused predominantly on use-related and environmental factors (Farrell and Marion, 2002; Hammitt et al., 2015). Few studies have investigated the influence of managerial actions, though they have considerable potential for modifying the roles of use-related and environmental factors (Leung and Marion, 1996; Marion and Leung, 2004; Marion, 2016). Among managerial factors, research attention has focused on design attributes, primarily trail grade, and less frequently on trail slope alignment, tread drainage, and tread surfacing (Olive and Marion, 2009). For example, we found only two studies that evaluated the effectiveness of alternative tread drainage actions on soil loss (Marion, 1994; Grab and Kalibbala, 2008).

Sustainable trails are designed, constructed, and managed to accommodate their intended types, amounts, and seasons of use to provide high quality visitor experiences while protecting the trail infrastructure and adjacent natural resources. Existing research suggests that trail design, a trail's siting and alignment relative to topography and soils, is the most important factor influencing long-term sustainability (Marion, 2016; Marion et al., 2011; Olive and Marion, 2009; Ramos-Scharrón et al., 2014). Poorly designed trails deteriorate quickly under traffic, unnecessarily degrade the local environment, and are more difficult to use and manage, requiring substantially greater maintenance effort (Marion and Leung, 2004). Such trails are unsustainable unless extensively hardened, or tread degradation is likely to be severe and unacceptable.

This paper investigates the influence of selected managerial factors on trail soil loss through regression modeling and analyses of trail datasets from research conducted at the Hoosier National Forest (Indiana), Big South Fork National River and Recreational Area (Tennessee), and Acadia National Park (Maine). Data from these protected natural areas are used to evaluate similarities and differences in findings and to gain improved insights from different environmental settings and trail design and management practices.

2. Literature review

This review focuses on several managerial factors pertaining to the design and maintenance of sustainable trails, including trail grade, trail slope alignment angle, trail drainage, and trail substrates.

2.1. Trail grade and slope alignment

The slope or grade of a trail and its alignment relative to local topography are determined when it is laid out or created by visitor use, hence our inclusion of these attributes as managerial factors. Numerous studies have examined the influence of trail grade on tread soil loss and found a strong positive relationship (Farrell and Marion, 2002; Helgath, 1975; Olive and Marion, 2009). The authors note that statistical modeling by Dissmeyer and Foster (1984) reveals that soil erosion rates become exponentially greater with increasing trail grades, particularly above 10%. These findings can be explained by the greater velocity and erosivity of running water on steep slopes as shown in soil erosion models (Renard et al., 1997), and by increased slippage or gouging of feet, wheels, and hooves that displace soil down-hill (IMBA, 2007; Leung and Marion, 1996).

Numerous trail maintenance books offer guidance regarding maximum trail grades to minimize soil loss on trails, though none appear to be based on empirical data from scientific studies. We believe this to be a significant limitation in our current literature which highlights the need for an expanded program of trail science research. Some recommended maximum trail grades are 10% (Hooper, 1988), 12% (Agate, 1996; Hesselbarth et al., 2007; National Park Service, 2007), and for horse trails 9% (Vogel, 1982), 10% (Wood, 2007), and 5–12% (Hancock et al., 2007). These values are generally applicable for medium-textured soil substrates; many authors suggest steeper grades are acceptable over short distances, particularly if they have sufficient native or applied rock to deter tread displacement and erosion. Regression modeling by Olive and Marion (2009) found trail grade to significantly influence soil loss, with substantially greater soil loss at grades above 11%.

Parker (2004) provides guidance on maximum permissible tread lengths between trail dips and crests based on trail grade and substrate texture, though empirical data are not cited as a basis. The IMBA (2007) suggests a maximum sustainable grade as low as 5% for sandy/fragile soils, 10% for loamy/mixed textures, and 15% for rocky or durable soils. Again, no empirical data are cited as a basis for this guidance. This reference and the widely cited Trail Solutions book (IMBA, 2004) highlight the need to consider an array of variables in determining maximum sustainable grades, including trail alignment relative to landform slope (discussed below), frequency of grade reversals (tread lengths), soil and vegetation type, and type or number of trail users and trail difficulty.

IMBA (2004, 2007) promotes the “10% Average Guideline,” which suggest that trails with an average or overall grade of 10% or less will generally be sustainable with respect to soil loss. The average grade is calculated by summing elevation gain for sections of the trail that are consistently climbing, dividing by trail length, and multiplying by 100. This guidance can be difficult and/or inaccurate to apply when a trail alternately ascends and descends or when exceptionally steep trail grades are offset by large portions with low grades. Such guidance is most easily applied when comparing alternative trail alignments on topographic maps or with Geographic Information System (GIS) software; application in the field with clinometers, tape measures, and flagging tape presents greater difficulty.

A trail design factor that receives considerably less attention by trail professionals and scientists is what Leung and Marion (1996) term trail slope alignment angle (TSA). This indicator is more easily assessed with a compass as the smallest difference in bearings between the prevailing landform slope (aspect) and the trail's alignment. The TSA of a contour-aligned trail would equal 90°, while a “fall-line” trail (aligned congruent to the landform slope or direction followed by water drainage) would have a TSA of 0°. Trail alignments with low TSA's more directly ascend slopes and their adjacent side-slopes are relatively flat in reference to the plane of the trail tread (Fig. 1). Such alignments are highly susceptible to degradation because initial traffic displaces or compacts soil, incising the tread, which then transports water that contributes to erosion in sloping terrain and muddiness in flat terrain (Basch et al., 2007; Olive and Marion, 2009; Wimpey and Marion, 2010). Tread water drainage features are difficult or impossible to install and are often ineffective in removing intercepted water from treads with low slope alignments (TSA of 0-22°) because both side-slopes are higher in elevation (Fig. 1) (Marion and Leung, 2004; Wimpey and Marion, 2010). Additionally, the side-slopes of fall-aligned trails also offer no resistance to lateral visitor traffic, so trail widening is a common problem.

In contrast, trails that more closely follow the contour of the surrounding topography, termed "side-hill" trails, always have one lower side-slope to drain water from out-sloped treads or drainage features (Fig. 1). While side-hill trails generally have larger upslope watersheds and intercept more water than fall-aligned trails, it's substantially easier to shed water from side-hill treads. If treads become cupped or develop raised berms on the lower side, maintainers can generally excavate to drain tread water and deter soil loss or muddiness. The adjacent sloping side-hill terrain also naturally act to concentrate traffic on the tread, which effectively limits trail widening.

Regression modeling by Olive and Marion (2009) determined that TSA has "a major and robust influence" on trail soil loss, with fall-aligned trails significantly more susceptible to soil loss. TSA's influence on soil loss was more significant than trail grade, with regression modeling revealing a diminished but still significant "trail grade" influence after TSA was added to the regression model. Results from statistical modeling of soil loss supported earlier speculation by Leung and Marion (1996) that: "the importance of slope alignment angle increases in its significance as trail grade increases." The authors also found that horse and ATV use caused significantly greater trail damage by erosion on trails closely aligned to the fall-line than either hiking or mountain biking, with a suggestion to keep horse and ATV trail alignments greater than 48°. In summary, these studies reveal that increasing TSA values contribute to increasing trail sustainability, minimizing soil loss, muddiness, and tread widening. Furthermore, the positive influence of higher TSA values increases with increasing landform grade (less muddiness, trail widening, and soil loss), while the negative influence of lower TSA values increases with increasing trail grade (steeper fall-aligned trails erode more quickly) (Fig. 2).

While many trail guidance publications recommend side-hill trail alignments and include warnings to avoid routing close to the fall-line, most give this topic scant treatment relative to their substantially greater focus on trail grade. The IMBA publications (2004, 2007) highlight the traditional trail grade recommendations but also developed the "Half Rule" guidance, which recommends trail grades should not exceed half the grade of the landform being traversed. This guidance is widely applied for all types of trails but no research is cited in support of the selection of 50% versus some other value. Computed by dividing trail grade by landform grade, Half Rule slope-ratio values should not exceed 0.5 according to this guidance. A trail on a landform or "side-slope" grade of 20% should have a grade of $\leq$10%, which has the primary effect of preventing trails from being aligned close to the fall-line. Other organizations recommend more conservative slope-ratio guidance, suggesting a limit of 0.33 (Minnesota DNR, 2007). Slope ratios can be easily calculated in the field when flagging new trails, or assessed through point sampling surveys of existing trails to evaluate their potential sustainability. For example, our survey of trails in Great Falls Park, VA, found that half of all sample points had a slope ratio $\geq$0.75, indicating a large proportion of this trail network is aligned too close to fall lines (Wimpey and Marion, 2011).

The Half Rule is similar to TSA in that it assesses how a trail is aligned relative to the landform slope, employing the quotient between trail and landform grades instead of the smallest difference between their compass bearings (azimuths) (Wimpey and Marion, 2011). IMBA (2007) notes the need for exceptions to the

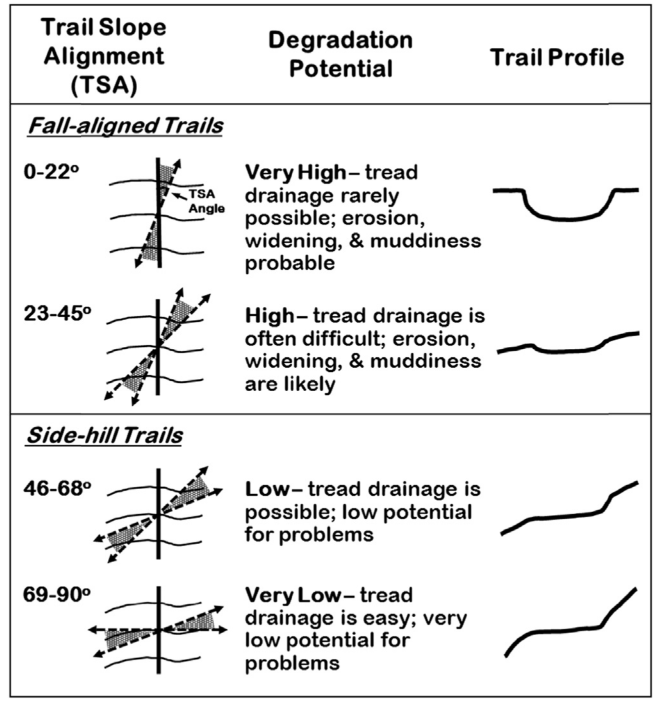

Fig. 1. Expected trail degradation potential and trail cross-section profiles for four for four categories of trail slope alignments ranging from fall-line trails (0-22°) to contour-aligned side-hill trails (69-90°). In diagrams on left, dashed lines depict trail alignments, solid lines depict the prevailing landform grade or aspect, and curved lines depict contour lines.

Half Rule on particularly steep landforms, for example a landform with 50% grade would allow an unsustainable 25% grade trail. They advocate applying a maximum trail grade in such instances, recommending that most trail grades should "never exceed 15%, even if a steeper trail would meet the Half Rule" (IMBA, 2007).

2.2. Trail drainage

One objective of sustainable trail design and management is to create trails that are hydrologically invisible, with a goal of minimizing the diversion and concentration of surface water runoff. Tread drainage features have been a traditional method for removing water from trails, generally constructed by excavating tread substrates to create an angled drainage ditch (Birchard and Proudman, 2000; Birkby, 2005; Demrow and Salisbury, 1998). These include drainage dips constructed with a ditch backed by a mound of soil, water bars backed and armored with wood or stonework to extend their life (Fig. 3a), and less commonly, flexible rubber "wheel friendly" water bars (Minnesota DNR, 2007). These features are installed during construction or subsequent maintenance to intercept and drain surface runoff from treads, with the number and spacing of features matched to trail grade and substrate erosivity (Parker, 2004; Forest Service, 1991).

Minimal research has been applied to evaluate the efficacy of tread drainage features. A survey of 528 km of hiking and horseback trails in Great Smoky Mountains National Park rated the perceived efficacy of drainage dips (unarmored) and water bars (armored with rock or wood, Fig. 3a) in removing water from treads (Marion, 1994). A total of 4137 drainage dips and 3804 water bars were assessed (mean = 10.6/km and 6.6/km, respectively), with a larger percentage of water bars judged to be very effective (44%) compared to drainage dips (20%). While factors such as rating subjectivity and the relative ages, quality of installation, and annual

Fig. 2. a) Steep fall-line trails (TSA <22°) erode rapidly. b) Side-hill contour-aligned trails (TSA >69°) resist widening, muddiness, and soil loss. c) TSA is less influential in flat terrain where trail widening and muddiness are common problems. Photos by Jeff Marion.

maintenance confound such evaluations, the extremely large number of features evaluated and considerable diversity in soil types, elevations, trail grades and expertise of installers and maintainers lends veracity to this finding. Mende and Newsome (2006) assessed the condition and effectiveness of tread drainage features on 32.7 km of trails in Stirling Range National Park, Western Australia. While 87% of the water bars were judged to be in good condition, only 13% were judged to be very effective in removing water from treads, suggesting improper and unskilled installation. When tread drainage features fill up and fail the slope-length increases, thus increasing soil erosion during rain events. Dixon and Hawes (2015) noted that water bars had prevented erosion along some segments, while active erosion occurred within segments that lacked such features.

Water can also be drained from side-hill trails by shaping the tread (out-sloping, in-sloping, or crowning) (Birchard and Proudman, 2000; IMBA, 2004; Parker, 2004) (Fig. 2b). Authors most commonly recommend out-sloping treads to the downhill side 2–3% for hiking trails and 5% for mountain biking trails to promote tread drainage (Minnesota DNR, 2007). However, all tread shapes constructed to shed water rarely maintain their constructed profiles over time: tread compaction, soil displacement from traffic, soil erosion, and the development of a berm along the lower trail edge soon act to keep water on the trail (Parker, 2004). Rocky tread substrates help to retain self-draining tread shapes over time but an appropriate density of grade reversals or the construction and maintenance of tread drainage features is additionally necessary.

The "Best Management Practice" for removing water from trails involve designing side-hill trails that roll slightly up and down along the contour, or that have substantial grade reversals designed and built into the tread (Fig. 3b) (IMBA, 2004, 2007). All water is forced off of treads when the trail grade temporarily reverses and periodic maintenance is generally not necessary. Tread grade reversals are the most permanent, effective, and sustainable practice for draining water from trails (Hesselbarth et al., 2007; Marion and Leung, 2004; Parker, 2004). Known variously as terrain dips, rolling grade dips, or simply grade reversals, these features temporarily reverse the trail grade to shunt all water from treads and require little maintenance (IMBA, 2007; Hesselbarth et al., 2007).

2.3. Trail substrates

Soil texture is another core factor that substantially influences the sustainability of a trail to accommodate traffic without degradation. A wide range of soil particle sizes comprise trail treads, ranging from fine-grained clay, to silt, sand, and rock (gravel, stone, bedrock). Differing proportions of these constituents have widely varied properties relating to how easily trail substrates compact, are displaced by traffic, or are eroded by water or wind. Fine-textured substrates compact and resist displacement when dry but can retain and puddle water and promote muddiness when wet. Coarse-textured substrates are well-drained but more easily displaced by traffic (Parker, 2004), unless rock components are angular and/or large in size. The best tread substrates include a wide range of particle sizes, including angular rocks and gravel to support heavy traffic and resist displacement and erosion, sand to promote drainage, and silts and clay to act as binders promoting cohesion.

When trail design is constrained or insufficient to create a sustainable trail, managers can apply trail construction and maintenance practices, including application of stonework or gravel to harden trail treads (Fig. 4). Research has shown that trail substrates with a high rock or gravel content are less susceptible to soil erosion and better able to sustain heavy traffic, particularly by horses (Bryan, 1977; Weaver and Dale, 1978). A four-year study of primitive forest roads used for logging and recreation found that non-graveled roads lost 112 metric tons/ha/year of substrates while graveled roads lost only 13.5 metric tons/ha/year (Kochenderfer and Helvey, 1987). Tread substrates with substantial rock and gravel content are also less easily displaced by recreational traffic, and these materials can act as filters, retaining and binding finer soil particles (Aust et al., 2004).

Crushed gravel is a commonly used amendment on frontcountry trails but is considered less appropriate in backcountry areas, and generally inappropriate in wilderness unless locally-sourced. For example, hikers on a popular, highly accessible trail in Acadia National Park found the use of gravel and dimensional plank boardwalks to be acceptable, while hikers visiting a remote backcountry area disapproved of such treatments (Cahill et al., 2008). Managers on the Hoosier National Forest experienced substantial public opposition to the use of gravel to harden backcountry multi-use trails (Wadzinski, 2000). Aust et al. (2004) suggest that mixing gravel with native soil prior to application can be an effective practice for hardening trail treads while alleviating aesthetic objections.

Crushed gravel is an effective amendment on horse trails (Wood, 2007). When applied with the fines from the crushing process it forms a highly resistant tread substrate, particularly when dry. The material is more easily displaced when wet by the heavy weight of horse and rider. Its efficacy in limiting erosion on steeper trail grades has not been sufficiently investigated, though some guidance suggests it can be applied to slopes up to 16% when stone anchors and sufficient drainage are also incorporated (Footpath Trust, 1999). Additional means to increase efficacy include integrating the aggregate with geotextiles, using angular crushed stone with crusher fines retained, and shifting to coarser materials on steeper slopes (Meyer, 2002; Footpath Trust, 1999). However, coarser materials (>4 cm) can be harmful to horses and have lower trafficability to most trail users.

Various types of well-anchored rockwork, including tread armoring (stone pitching) and rock steps, are common tread hardening techniques used to deter erosion on steeper trail grades (Demrow and Salisbury, 1998; Footpath Trust, 1999) (Fig. 4a). This practice replaces erodible substrates with rockwork on wet or steeply graded trail segments particularly prone to erosion. No studies evaluating the long-term efficacy of employing rockwork to limit trail erosion could be found.

3. Methods

3.1. Study sites

Data presented in this paper are from three study areas (Fig. 5):

Hoosier National Forest (HNF) - located in south-central Indiana with 81,014 ha and 352 km of trails open to mixed uses. HNF visitation data from 2004 show that these trails received approximately 100,918 hikers, 32,625 horseback riders, and 3227 mountain bikers (Forest Service, 2005; Strout, 2005). The terrain is characterized by hardwood forests on rounded hills underlain by limestone, with loess soils that have silt loam textures.

Big South Fork National River and Recreational Area (BSF) — located in north-central Tennessee and south-central Kentucky with 50,990 ha and over 526 km of single and multi-use trails. BSF receives approximately 700,000 visitors annually (Marion and Olive, 2006), most of which use some portion of the trails to hike,

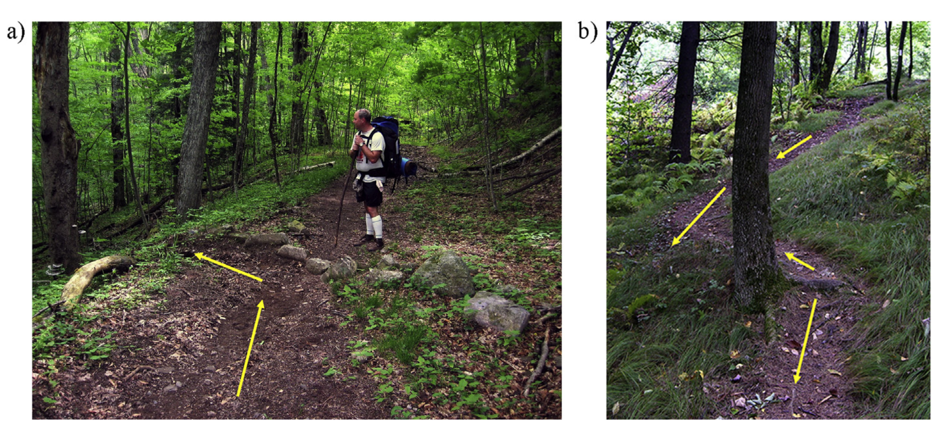

Fig. 3. a) This rock water bar is preceded by a ditch to drain water from the trail. b) Grade-reversals temporarily reverse the grade of the trail so that all water drains off; these rarely require maintenance. Photos by Jeff Marion.

a) b)


Fig. 4. a) Trails that must support heavy traffic, particularly by horses, can be armored with embedded rock (stone pitching). b) Crushed rock (gravel) also supports heavy traffic, though is more easily displaced when wet. Photos by Jeff Marion.

horseback ride, mountain bike, or ride ATV's. Predominantly hardwood forests cover a tableland underlain by resistant sandstone, shale, and dry sandy soils, carved by erosion into impressive cliffs, arches, chimneys and steep-walled gorges.

Acadia National Park (ANP) - located in the central coast of Maine with 13,300 ha and 193 km of hiking trails, most of which were crafted 90–130 years ago. ANP received approximately 2.2 million visitors in 2007 (Marion et al., 2011). The glacially shaped terrain is highly varied; beaches and cliffs along the rocky coastline give way to steep ridges of exposed granite bedrock and thin, coarse soils, interlaced with woodlands and open shrub communities.

3.2. Trail selection

In HNF, a random stratified sample of multi-use trails (14% of the forest's 352 km trail system) yielded 58 km with representative stratifications for three levels of use (low, moderate, and heavy) and tread substrate (graveled and non-graveled). In BSF, a random sample of multi-use trails (24% of the park's 526 km trail system) yielded 126 km of the park's trails and primitive recreational roads, selected using the park GIS database and the SPSS Random Sample procedure. At ANP all trails within the Mount Desert Island portion of the park were surveyed (100% of 193 km).

3.3. Field Procedures

For the sampled trails within each study area 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 (Marion and Olive, 2006). An interval of 152 m was used following guidance provided by Leung and Marion (1999). 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. At BSF, the percentage of this width with visible human-placed gravel was estimated to the nearest 5%. At HNF, the depth of human-placed gravel was measured at the center of each transect. At ANP, trail substrate class was assessed as natural, graveled, stonework, or bridge/boardwalk.

Soil loss at each transect was measured using a Cross-Sectional Area (CSA) method (Olive and Marion, 2009). A taut nylon line was stretched between the trail boundary stakes from their base at the ground surface. 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. Spreadsheet formulas were developed to calculate CSA based on these data. The total number of CSA soil loss measurements at each study area are: ANP (489), HNF (619), and BSF (827) for a total of 1935 measures.

Trail grade was assessed at sample points with a clinometer and TSA was assessed as the difference in compass bearing between the prevailing landform slope (aspect) and the trail's alignment at the sample point (Leung and Marion, 1996). The TSA of a contour-aligned trail would equal 90° while a "fall-line" trail (aligned congruent to the landform slope) would have a TSA of 0°. At HNF and BSF, tread drainage was assessed as the distance, in 7.6 m increments up to 30.5 m, to any tread drainage feature located in an upslope trail direction from the sample point. For more complete descriptions of sampling and field research methods, see the respective final research reports (HNF: Aust et al., 2004; BSF: Marion and Olive, 2006, and ANP (Marion et al., 2011).

3.4. Data analysis

Data were input into spreadsheets and imported into the SPSS statistical package for analyses. Multiple regression analyses were used to evaluate the influence of trail grade, slope alignment angle, tread drainage, and gravel (independent variables) on trail soil loss (CSA, dependent variable). Analyses were run separately for each study area. A stepwise method was used with the probability of F-to-enter of 0.05 (PIN) and the probability of F-to-remove of 0.10 (POUT). Two iterations of the equations were run, removing outliers whose standardized residuals exceed an absolute value of three. One-way analysis of variance (ANOVA) testing was used to evaluate the veracity of a trail Sustainability Rating developed to indicate the potential for soil loss on trails. This analysis employed the Least Significant Difference (LSD) post-hoc comparison test for mean values (alpha <0.05). Two-way ANOVA tests were used to evaluate the influence of tread drainage features and gravel application on soil loss. Use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

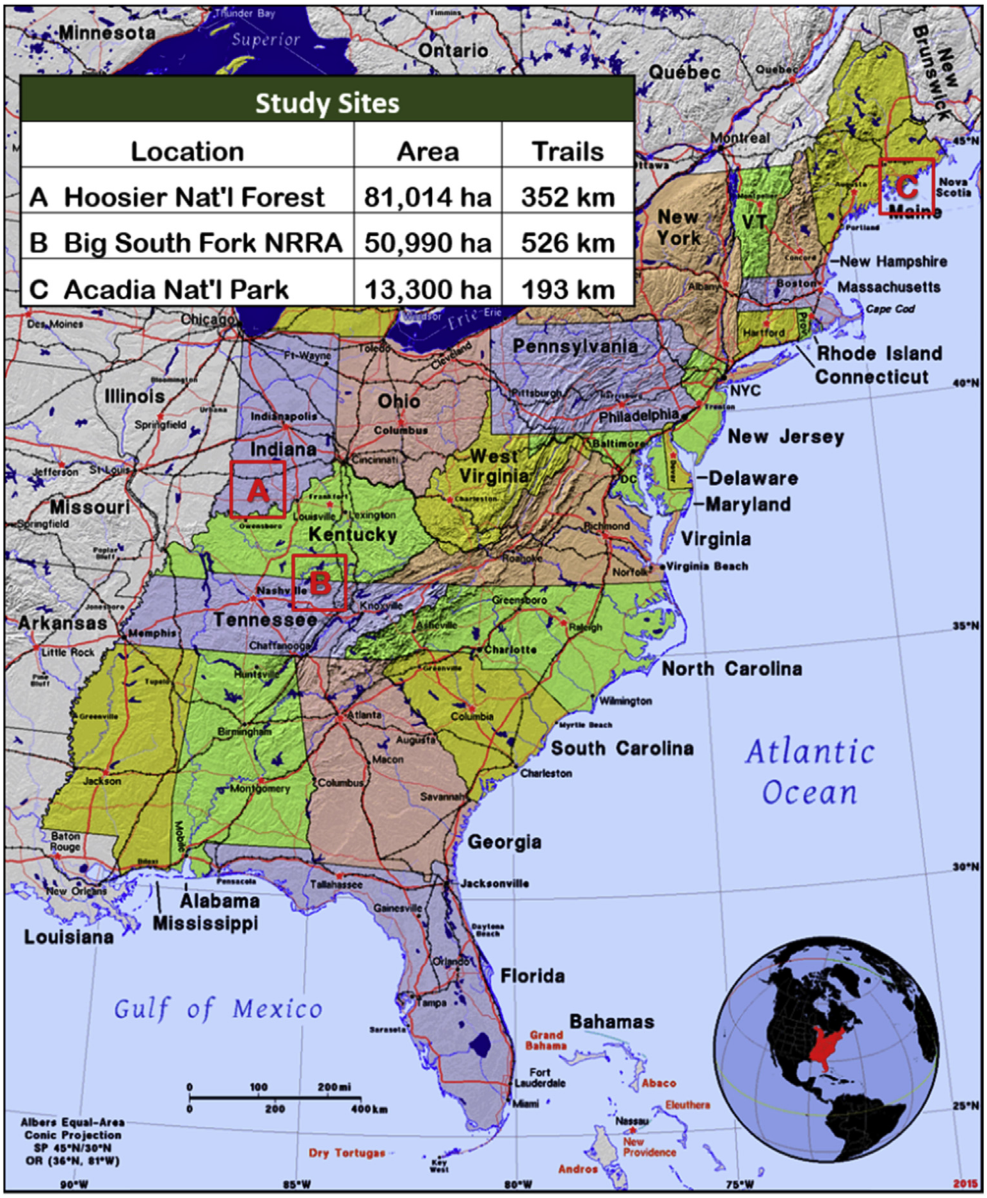

Fig. 5. Eastern United States showing locations of the three study areas.

4. Results

4.1. Evaluating trail design and maintenance

Trail surveys can efficiently provide a variety of information characterizing the sustainability of trails to accommodate use while minimizing degradation (Marion et al., 2012). Recreation ecology research and the trail design literature commonly cite trail grade as a principal trail design attribute, with recent research indicating the importance of TSA. Survey data from the study areas examined in this paper show substantial variation in both attributes for these three trail systems. Mean trail grade ranges from 4.3% for HNF, to 8.0% for BSF and 13.2% for ANP, and mean TSA values range from 32.4° for ANP, 54.5° for BSF, and 61° for HNF. Table 1 presents the distribution of trail grade values in a cross-tabulation with TSA values, showing the percentage of the surveyed trail systems within each of 12 trail grade/slope alignment categories. The number of categories and their boundaries were selected based on examinations of data distributions and extensive statistical modeling and testing from all three study areas.

To summarize the implications of these trail design attributes and values, we developed a *Trail Sustainability Rating* index and assigned it to the matrix of trail grade and TSA values (Table 1). Applying guidance derived from this study and the published research, trail design and maintenance books, and our professional judgment, we began by assigning as "neutral" trail segments with extremely low grades (0–2%), which are least likely to experience tread soil loss. However, we emphasize that trail segments with low grades located in flat terrain are more susceptible to muddiness and trail widening, two other common types of trail impact. Next, we suggest that optimal or "Good" trail alignments are those with grades of 3–10% and TSA values greater than 30°. A "Poor" sustainability rating was assigned to trails with optimal grades (3–10%) but the poorest TSA alignments (0-30°), and to trails with alignments over 30° but grades of 11–20%. Finally, trails with exceptionally steep grades (>20%), or with moderately steep grades

(11–20%) but low TSA alignments (0-30°), received a "Very Poor" trail sustainability rating (Table 1).

The Trail Sustainability Ratings reveal that 83% of the HNF horse trails have good or neutral designs with respect to grade and TSA, with only 3.7% rated as very poor (Table 1). At BSF, 68.4% of the trail system has sustainability ratings of good or neutral, with 6.9% rated very poor. Largely due to higher percentages of trails in the lowest TSA category, the ANP trail system has substantially lower sustainability ratings, including less than half (48.1%) with good or neutral ratings and 18.3% with very poor sustainability ratings.

The veracity of the Trail Sustainability Ratings in reflecting the soil loss potential of alternative trail alignments was tested with ANOVA for CSA soil loss. The tests for all three study areas were statistically significant ($p < 0.001$), with post hoc testing of mean values revealing significant increases in soil loss for trail alignments with Sustainability ratings progressing from neutral to poor, and from poor to very poor (Table 1). Differences in CSA mean values for the good and neutral Sustainability Ratings were mixed, as expected, given that the neutral rating was applied to alignments with potential to suffer from trail widening or muddiness, rather than soil loss.

Trail survey data also provided information to characterize trail maintenance actions, including the spacing of tread drainage features and application of gravel. No tread drainage features were located within 30 m of 75% of the sample points at HNF and within 92% of the sample points at BSF (drainage features were not assessed at ANP). U.S. Forest Service guidance on recommended drainage feature spacing by trail grade class for medium-textured soils was applied to the survey data for sample points on native soils on grades above 7% (Forest Service, 1991). Guidelines for grades below 7% could not be assessed because the spacing exceeded 30 m, our maximum assessment distance for drainage features (see Section 3.3 on Field Procedures). This guidance recommends spacing tread drainage features 23 m apart on trails with grades between 7.1 and 9%. For HNF trails, 97 of 133 sample points (72%) exceeded the Forest Service tread drainage spacing guidance; for BSF trails, 332 of 346 sample points (96%) exceeded the recommended spacing.

Gravel was found on trails previously or currently used as primitive roads, and on trails where it was applied to harden substrates, improving their ability to sustain higher levels of traffic or the greater weight and ground pressure of equestrian traffic. At

Table 1
Percentage of the surveyed trail systems by trail grade and slope alignment angle with Trail Sustainability Ratings.

Trail Slope Alignment	Study Area	Trail Grade 0-2%	3-10%	11-20%	>20%	Totals
0-30°	BSF	2.3	10.1	6.6	0.3	19.3
	HNF	8.9	7.5	3.5	0	19.9
	ANP	6.9	22.9	16.7	1.1	47.6
31-60°	BSF	6.0	17.9	8.4	0	32.3
	HNF	5.4	8.2	2.3	0.2	16.1
	ANP	2.4	8.7	6.0	0.4	17.4
61-90°	BSF	14.2	28.1	6.2	0	48.5
	HNF	42.6	17.9	3.5	0	64.0
	ANP	12.9	17.3	4.7	0	34.9
Totals	BSF	22.4	56.0	21.3	0.3	100
	HNF	56.9	33.6	9.4	0.2	100
	ANP	22.1	48.9	27.4	1.6	100

Study Area		Trail Sustainability Ratings[1] Good	Neutral	Poor	Very Poor	
	BSF	45.9%	22.5%	24.7%	6.9%	
	HNF	26.1%	56.9%	13.3%	3.7%	
	ANP	26.0%	22.1%	33.6%	18.3%	
F-value[2], df		Mean CSA Soil Loss (cm^2)				Sig.
22.0, 3	BSF	419[a]	486[a]	823[b]	1759[c]	.001
7.6, 3	HNF	1076[a]	885[b]	1204[a]	1639[c]	.001
7.7, 3	ANP	414[a]	403[a]	567[b]	712[c]	.001

1– Ratings were applied to the trail grade-TSA matrix above according to criteria shown in the text and illustrated with shading. The percent values below are the proportion of each study area's trail miles that received each Trail Sustainability Rating.

2 – ANOVA results, including F-value and degrees of freedom. Post hoc testing of mean values based on the Least Significant Difference t test. Means with the same letter are not significantly different (alpha=0.05)

HNF, graveled trails were intentionally selected as one-half of the sample population, all of which were equestrian trails. Mean gravel depth for these trails was 7.5 cm. Two-way ANOVA testing revealed a significant relationship between increasing distance to tread drainage features and increased soil loss ($F = 3.0$, $p = 0.050$, $df = 2$), but the effect of gravel application was not significant ($F = 2.2$, $p = 0.133$, $df = 1$), nor was the interaction term. The relationship between these variables is shown in Fig. 6, which shows the greater influence of drainage features on trails with native soils than for graveled trails.

At BSF, 55% of the sample points were located on native substrates, 28% had some gravel cover, and 17% were predominantly graveled. Equestrian trails were most frequently graveled, with some gravel found on mixed use trails and more rarely on hiking trails. ANOVA testing at BSF yielded similar results to HNF, with a significant relationship between tread drainage feature spacing and soil loss ($F = 3.3$, $p = 0.046$, $df = 2$), not significant for gravel application ($F = 0.09$, $p = 0.768$, $df = 1$), and a non-significant interaction term.

The efficacy of gravel application to limit erosion on steeper trail grades was also investigated. Two-way ANOVA testing of HNF data revealed significant relationships between soil loss and gravel application ($F = 9.4$, $p = 0.002$, $df = 1$) and trail grade ($F = 14.3$, $p < 0.001$, $df = 2$), with a significant interaction ($F = 3.1$, $p = 0.044$, $df = 2$). As depicted in Fig. 7, soil loss increases significantly with trail grade on native soils. However, this relationship is weak on graveled trails, appearing to suggest that gravel is effective in reducing soil loss on trail grades over 15%. However, discussions with managers revealed that gravel placed on steep trail grades commonly suffered downhill displacement problems in areas of heavy horse traffic. Such locations are visited more frequently by maintenance staff to regrade these problem segments, often shifting gravel back upslope and/or adding more gravel. We conclude that the CSA soil loss for graveled trails at 16–50% grades would likely be much higher than depicted in Fig. 7 in the absence of such maintenance work.

4.2. Understanding trail degradation

The relative influence of trail grade, TSA, gravel application, and tread drainage feature spacing on CSA trail soil loss was evaluated through multiple regression analyses. These attributes are under managerial control through trail design and maintenance. Table 2 presents multiple regression results. For ANP, trail grade and TSA were retained and are highly significant predictors of CSA soil loss. For HNF and BSF, trail grade and TSA were also the most significant predictors of soil loss, though distance to tread drainage features remained in the final models (Table 2). Note that gravel application was non-significant in the final equations, indicating the higher influence of the three included factors.

A graph illustrating the relationships of the two most significant factors that influence CSA soil loss, trail grade and TSA, is shown in Fig. 8 using BSF data. On fall-line trails (TSA <23°) there is a substantial difference between the amount of soil loss across all trail grades compared to those with alignment angles over 23° (Fig. 8). Soil loss is particularly pronounced on fall-line trails with trail grades above 16%. Coincidentally, the influence of trail grade on soil loss appears to be less substantial on trails with TSA values exceeding 22°.

5. Discussion

Unlike the management guidance for subjects like fisheries, wildlife, and recreation management, the current trail design and maintenance literature appears to not be "science-based," with Best Management Practices derived from research findings published in the peer-reviewed literature. Few of the current publications mention linkages between the guidance presented and research studies, or include citations referencing scientific literature. As an example, the widely disseminated and applied IMBA "Half Rule" (IMBA, 2007) was not derived from research, nor has it been evaluated by an empirical study. Such guidance is being widely applied in the U.S. and internationally; should it not be based on or evaluated by trail science research?

This study and others in the recreation ecology field examine the environmental impacts of visitation to protected natural areas

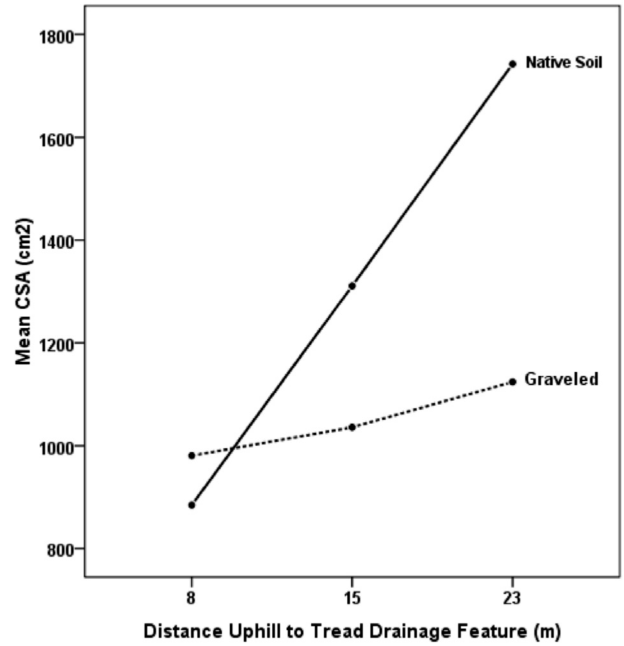

Fig. 6. Soil loss on HNF trails as influenced by graveling and proximity to tread drainage features.

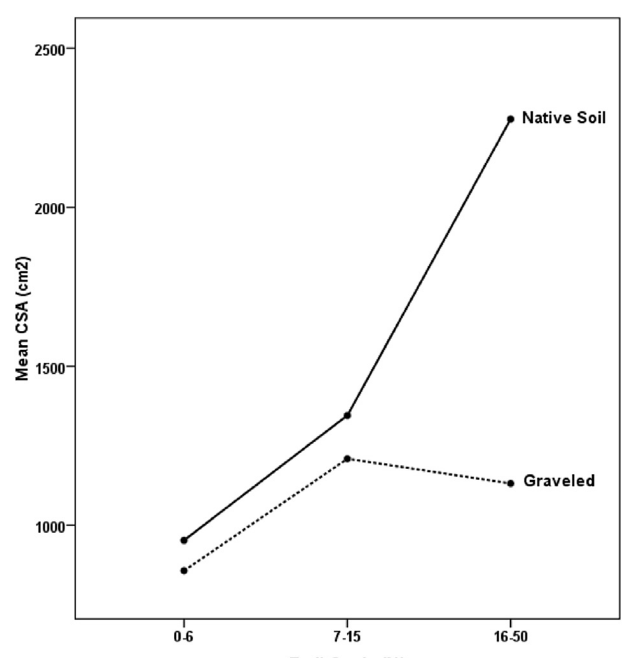

Fig. 7. Soil loss on HNF trails as influenced by trail grade and application of gravel.

Table 2
Multiple regression results evaluating the influence of trail grade, trail slope alignment (TSA), and tread drainage feature spacing on soil loss assessed on recreational trails.

Variables	Protected natural area		
	HNF	BSF	ANP
Trail Grade (%)	45.4[a] (0.000)	17.2 (0.000)	5.9 (0.006)
TSA (deg)	−2.1 (0.039)	−9.9 (0.000)	−1.6 (0.004)
Tread Drainage (m)	6.1 (0.074)	14.8 (0.022)	N.A.
Constant	722.9	524.7	482.1
Adjusted R^2	0.09	0.11	0.05

[a] Unstandardized CSA coefficients, cm^2.

to provide a scientific basis for managing visitor use sustainably – avoiding impacts when possible and minimizing those that are unavoidable. While recreation ecology studies with findings relevant to sustainable trail design and management have been conducted, funding has been limited and some critical topics have not been fully evaluated (Marion et al., 2011; Marion, 2016). Nevertheless, there is a growing body of applicable literature available that can assist the trail community in designing and managing trails that will better accommodate a diverse array of trail activities while resisting degradation, including the perennial problems of trail soil loss, muddiness, and widening (Dixon and Hawes, 2015; Farrell and Marion, 2002; Nepal, 2003; Olive and Marion, 2009; Pickering et al., 2010; Ramos-Scharrón et al., 2014; Wimpey and Marion, 2010).

Results from this study included trail measurements characterizing trail design, construction, maintenance, and conditions from National Park Service and U.S. Forest Service areas. A surprisingly large percentage of the trail systems in these areas would be classified as "unsustainable" by the existing management and scientific literature. For example, the percentages of the sampled trail systems for these protected areas that exceed a 10% grade range from 9.6 to 29% (Table 1). Similarly, the percentage of trail miles located in flat terrain (0–2%) that are highly susceptible to muddiness and trail widening range from 22 to 57%. Finally, as noted in the Literature Review, trail alignments close to the fall-line are extremely difficult to drain water from, contributing to excessive soil loss, muddiness, and widening. The percentages of the sampled trail systems with TSA values < 30° range from 19 to 48% (Table 1).

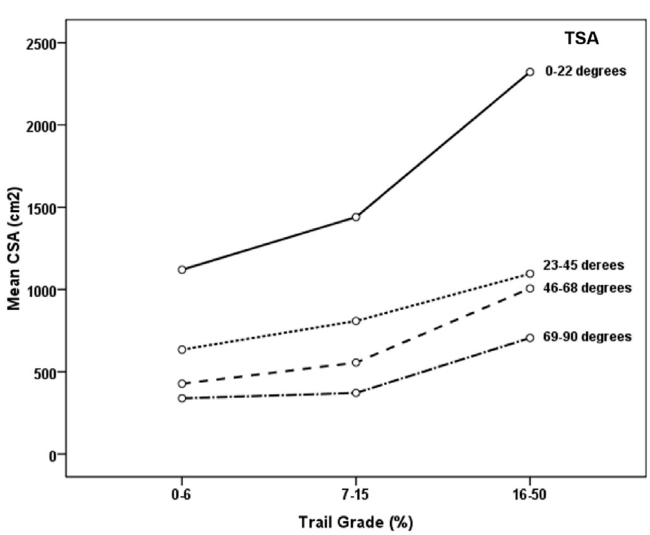

Fig. 8. Soil loss on Big South Fork NRR trails as influenced by trail grade and trail slope alignment angle.

Based on this study we propose a set of Trail Sustainability Ratings to guide and evaluate proposed and existing trail alignments and designs:

Trail Sustainability Rating	Trail grade and trail slope alignment criteria
Good:	Trail grade of 3–10% and TSA >30°
Neutral:	Trail grade of 0–2%
Poor:	Trail grade of 3–10% and TSA of 0–30°, trail grade of 11–20% and TSA >30°
Very Poor:	Trail grade of 11–20% and TSA of 0–30°, and trail grade of >20%

With respect to soil loss on trails, these proposed Trail Sustainability Ratings are consistent with and supported by the recreation ecology and the trail management literature presented in the Literature Review section, and by the statistical testing of data from the three protected areas evaluated in this study (Table 1). For example, substantially and significantly greater amounts of soil were lost from the treads of each study area between trail segments rated Good or Neutral (combined) and Poor, and between Poor and Very Poor. We emphasize that this study did not evaluate or validate these proposed ratings with respect to two other important forms of trail degradation: trail muddiness and widening. We suggest that further research and evaluations for additional forms of trail degradation are needed to validate these ratings.

Multiple regression analyses found trail grade to be a highly significant predictor of soil loss in all three study areas (Table 2). Higher trail grades showed substantially increased soil loss (Fig. 8), particularly as grades exceeded 15%, as expected based on the research by Dissmeyer and Foster (1984). ANP findings were similar, except that segments with low grades (0–4%) had similar low levels of soil loss. At HNF, as trail grade increased from 0-6% to 7–15% soil loss also increased (Fig. 8). Soil loss continued to increase substantially, particularly on native substrates with grades greater than 15%.

Regression analyses also found TSA to be a highly significant predictor of soil loss in all three study areas (Table 2), even when including and accounting for the strong influence of trail grade. This can be seen in Fig. 8 with the substantially greater soil loss depicted by the 0-22° TSA line for each trail grade category, with similar results from ANP except for low trail grades. At both protected areas the influence of TSA increased with increasing trail grade, i.e., soil loss on trails is particularly pronounced on steep fall-line trails. Coincidentally, soil loss is quite low on trails that are aligned close to contour lines (Fig. 8). In summary, this regression modeling indicates that TSA is as influential as trail grade on soil loss; draining water from fall-aligned trails is inherently difficult to accomplish and maintain. We suggest additional studies to validate this finding. Our examination of the current management literature on trail design and sustainability guidance reveals a substantially greater emphasis on trail grade. While a few references advise trail designers to avoid the fall line or apply the Half Rule (which prevents fall-line alignments), many others barely mention this topic. Based on this study, current trail design guidance underestimates the relative influence and importance of TSA as compared to trail grade.

Study findings also point to the strong influence of tread drainage features and gravel application in reducing soil loss on trails. Our findings indicate these attributes are important, but less influential than trail grade and TSA. However, we emphasize that trail segments with sub-optimal grades or TSA values are more sustainable if they have excellent drainage characteristics and rocky or gravel substrates. For example, a very steep side-hill trail with an out-sloped tread or closely spaced drainage features, or a steep fall-line trail predominantly on rock can be highly sustainable. These options are available to trail managers seeking to provide challenging trail experiences while also protecting natural resources.

In this study, trail measurements revealed substandard tread drainage feature densities at HNF and BSF (not assessed at ANP). Other studies have also reported this finding. Even when drainage dips or wood and stone water bars are present in sufficient densities they are ineffective unless properly installed and frequently maintained. Some disadvantages of these features are that they: 1) can be an obstacle contributing to trail widening and bicycle accidents, 2) are degraded over time by traffic and filled in by sediment deposition, 3) can divert larger volumes of runoff and sediments into water bodies, and 4) are frequently incorrectly installed (too short or low, improper angle, poorly anchored rocks or logs) (Hesselbarth et al., 2007).

We conclude that these "traditional" drainage features are less effective and desirable than full-tread grade reversals, which are extremely effective and require little to no recurring maintenance. Other methods of tread drainage, including elevated/crowned, and in- and out-sloped tread shaping, are also only effective when initially constructed and regularly maintained (Parker, 2004). Over time, soil loss and displacement and development of a higher trailside berm will reduce or negate their efficacy. However, we are unaware of any studies that have empirically evaluated the efficacy of these options; research is needed.

5.1. Conclusion

In summary, this research reveals that trail grade and slope alignment angle appear to have the greatest influence on soil loss from recreational trails. A Trail Sustainability Rating System is offered to trail designers and managers to more clearly guide the development and evaluation of trail sustainability and to illustrate the tradeoffs between these influential factors. In most instances a limited number of trail segments will be identified as "unsustainable" and managers can replace them with alternative reroutes that feature side-hill alignments and low grades. If reroutes are not an option, rockwork, graveling and installing additional drainage features can be effective actions to decrease trail soil loss. While grade reversals are a preferred tread drainage option, measures like out-sloped treads, drainage dips, and water bars can also be effective, though only when frequently maintained. We note that trail segments supporting higher impact uses, such as horses and motorized traffic, require greater adherence to sustainability guidelines, and in particular, can benefit from larger amounts of substrate rock or gravel application.

This research suggests that sustainably designed and well-maintained trails can substantially avoid or minimize tread soil loss, enhancing physical and managerial sustainability. The full application of these management actions should, in most instances, accommodate recreational traffic within acceptable levels of resource degradation, alleviating the need for use reduction and enhancing social sustainability.

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