



Sediment Availability and Erosion Rates on Off-Highway Vehicle Trails in the Ouachita Mountains, USA

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Research Impact Statement: The annual erosion rate for an off-highway vehicle trail system in the Ouachita Mountains is quantified as 75 to 210 tonne ha⁻¹ yr⁻¹ using both sediment availability and sediment traps.

ABSTRACT: Factors influencing sediment availability are assessed and erosion rates are quantified for an off-highway vehicle (OHV) trail system in the Ouachita Mountains of Arkansas. As of May 2012, the Wolf Pen Gap trail system included 77.0 km of "trails" which consist of county roads; open and closed Forest Service roads; and open and closed OHV trails. For a given trail length, the sediment volume available to be eroded is determined by bare trail width and sediment depth. Four condition types are defined that group trail sections based on statistically different trail widths or depths. Trail construction method appears to influence sediment availability differences more than erosion potential (as indexed by trail slope gradient and length). The range for annual trail erosion rates is estimated as 75 and 210 tonne/ha/yr. The high and low rates are obtained using two independent methods. The 210 tonne/ha/yr rate is computed from mean sediment capture at 30 sediment traps installed for 0.5–1.0 year. The 75 tonne/ha/yr rate is computed assuming all available trail sediment measured in a one-time sampling is eroded over the next year. We argue in support of this assumption and suggest both rate values may be conservative. Trail erosion rates and sediment trap observations indicate frequent trap cleanout will be needed to continue sediment capture from All Terrain Vehicle trails.

(KEYWORDS: off-highway vehicle; trails; erosion; sediment; watershed management.)

INTRODUCTION

The Wolf Pen Gap (WPG) Trail Complex in Polk County, Arkansas, is a designated off-highway vehicle (OHV) use area within the Ouachita National Forest (ONF, Figure 1). The WPG Trail Complex is emblematic of the challenges inherent in balancing the desire to provide recreation opportunities to OHV users and promote related economic benefits to local communities, against the mandate to prevent adverse environmental impacts. Created in the early 1990s, use of the trail complex has grown from an estimated 8,000–10,000 users per year in 1998 to >13,000 users

per year in 2010 (USDA Forest Service 2013). Since the late 1990s, concerns have developed about potential on-site sediment impacts from the trail system as well as downstream impacts to threatened and endangered mussel species in the Ouachita River (USDA Forest Service 2005). Information on trail sediment availability and erosion rates is needed by resource managers to evaluate the magnitude of the erosion problem and to plan effective practices to control erosion.

This study seeks to address this information need using data obtained from the WPG trail system. Our primary objectives were to (1) assess how factors such as trail dimensions, slope, and construction type

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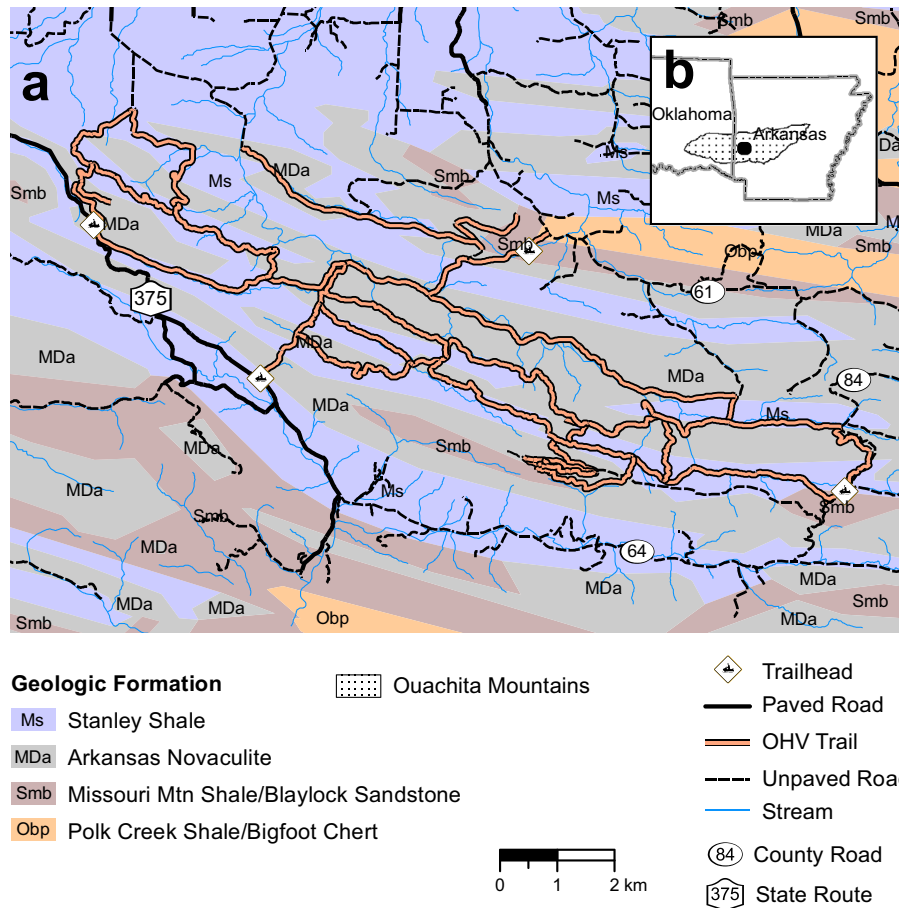


FIGURE 1. The Wolf Pen Gap (WPG) Trail Complex showing (a) active trail system extent and underlying geology and (b) location within Arkansas and the Ouachita Mountains. OHV, off-highway vehicle.

affect sediment availability; (2) quantify sediment availability within the trail system; and (3) to quantify trail erosion rates. Erosion rates are estimated using two methods: (1) direct measurement of eroded sediment from sediment traps; and (2) basing erosion on available sediment. Erosion rate estimates are also used to briefly discuss the source of trail sediment (trail prism vs. surrounding forest) and the frequency of sediment trap excavation needed to maintain trap efficiency.

The term "OHV" refers to a wide variety of 2- and 4-wheel drive vehicles used for travel on unpaved roads, trails, and cross-country. As used here, OHVs include all-terrain vehicles; utility or recreational OHVs (UTVs, ROVs, and side-by-sides, but exclude snowmobiles); off-highway motorcycles; and highway-legal trucks and sport utility vehicles. We will use the term "ATV (All-Terrain Vehicle)" as a general term to include all of the above except highway-legal vehicles. This distinction is helpful for characterizing which vehicle types are referenced.

Recreational use of OHVs is a large and growing activity in the United States (U.S.). Cordell et al.

(2008) estimated that by 2003 over 8 million ATVs were owned and that by 2007 more than 19% of all persons 16 or older had participated in OHV recreation nationwide, with much of the use occurring on public lands. In Arkansas and Oklahoma, the two states which encompass the Ouachita Mountains, ATVs are extremely popular. In 2007, more than half a million OHV users were identified in both Arkansas (557,100) and Oklahoma (695,500), which represented about 25% of both state populations age 16 and older (Cordell et al. 2008). Increased OHV use has led to growing concerns about undesirable environmental impacts where such use occurs.

PREVIOUS STUDIES

As at the WPG Trail Complex, unpaved forest roads are often used or repurposed as OHV trails. The impacts of logging and other unpaved forest roads on runoff, erosion, and sedimentation have long

been recognized and studied, and several recent reviews are available (Jones et al. 2000; Eisenbies et al. 2007; Neary et al. 2009; Robinson et al. 2010; Anderson and Lockaby 2011). Past studies have found erosion rates for logging roads in the Ouachita Mountains range from 55.4 to 90.0 tonne/ha/yr, while both lower and higher rates are reported for Virginia Piedmont roads depending on the surface type (Table 1).

Several studies have found that ATV impacts can differ from those of other types of trail and unpaved road use (see below). While considerable research has been done on ATV trails in dryland environments, particularly in the western U.S. (Ouren et al. 2007), the studies briefly reviewed below focus on ATV trails in humid forested environments.

In the steep, hilly forestlands of southern Ohio, Sack and da Luz (2003) found increased soil compaction and net erosion on ATV trails during the riding season. While ATV, hiking, and horse trails all showed compaction relative to adjacent forest soils, compaction was more pronounced on the ATV trails. Differing impacts between trail use types were also found by Olive and Marion (2009) in the forested river gorge terrain of north-central Tennessee and south-central Kentucky. They concluded that horses and ATVs have greater erosional impacts than hiking, mountain bicycles, and highway-legal vehicle traffic.

Studies in humid mountain forests using both direct measurements and modeling have determined that erosion rates from ATV trails vary widely. On the low end, Riedel (2006) estimated an erosion rate of 1.96 tonne/ha/yr for a single, lightly used OHV trail segment in northeastern Georgia. Erosion was determined from stream deposition of tracer grains over a three-month summer period. On the high end, Sack and da Luz (2003) found erosion rates on ATV trails as high as 2,090 tonne/ha/yr in southeastern Ohio. They used repeat cross section measurements on four similar trail segments during a three-month fall period with normal use, and after the following three-month winter closure. Working in the same terrain and using similar methods, Albright (2010)

measured a mean erosion rate of 313 tonne/ha/yr. In central Alabama, Ayala et al. (2005) determined a 30-year mean erosion rate of nearly 127 tonne/ha for an OHV trail using the hillslope version of the Water Erosion Prediction Project (WEPP) model. While Ayala et al. (2005) found that WEPP predictions compared well to those predicted from measured suspended sediment loads, Albright (2010) found that both the hillslope WEPP and WEPP:Road models underestimated the measured erosion rates by 43%–98%. No doubt differences in methods account for some of the variability apparent in past results, but differences in site characteristics and OHV usage may also be important.

The simple occurrence of ATV use appears to affect erosion more than the intensity of ATV use. Foltz (2006) found that the greatest differences in erosion and soil loss were between areas used by ATVs and those with no use, as opposed to between various levels of ATV traffic. Meadows et al. (2008) studied a progression from low to high disturbance classes associated with increasing ATV traffic at seven U.S. national forests. They found that runoff and sediment production increased by 56% and 625%, respectively, following any level of disturbance compared to undisturbed conditions. The details of ATV and tire design (within the category of ATVs, as opposed to ATVs compared to other vehicles) did not have major effects on disturbance. Meadows et al. (2008) also found that presence or absence of ATV traffic was more important than the intensity of trail use.

Erosion is a natural process in forests, and to judge the significance of OHV-related erosion, it is useful to know what erosion rates are within undisturbed forest stands. Unfortunately, we could not locate any published attempts that directly measure surface erosion processes on hillslopes in the Ouachita Mountains. However, two different sets of data are available that allow forest erosion rates to be approximated. The first uses the annual erosion rates predicted using the Universal Soil Loss Equation (USLE) for the Ouachita Mountains land resource area (Dissmeyer and Stump 1978) based on

TABLE 1. Erosion rates on unpaved forest roads similar to the WPG trail system.

Location	Erosion rate (tonne/ha/yr)	Description	Source
Ouachita Mountains, Arkansas	55.4	Four road segments monitored for 17 months; gravel surface; traffic allowed	Miller et al. (1985)
Ouachita Mountains, Oklahoma	91.0	Four segments monitored for 12 months; new gravel surface; traffic allowed	Vowell (1985)
Piedmont, Virginia	10.0–16.0	Four road sections with new gravel surface; traffic excluded	Brown et al. (2013)
Piedmont, Virginia	34.0–297	Five road sections with new native surface; traffic excluded	Brown et al. (2013)

TABLE 2. Annual erosion rate estimates for undisturbed forested sites in the Ouachita Mountains.

Erosion rate (tonne/ha/yr)	Estimation method	Source
0.0022	Universal Soil Loss Equation ¹ (USLE) using lowest factor values for Ouachita Mountains Land Resource Area.	Dissmeyer and Stump (1978)
0.18	USLE using average factor values for Ouachita Mountains Land Resource Area.	Dissmeyer and Stump (1978)
6.1	USLE using highest factor values for Ouachita Mountains Land Resource Area.	Dissmeyer and Stump (1978)
0.016	Mean sediment yield computed over nine-year period from stormflow runoff measured at outlet from three headwater basins all < 0.7 ha.	Lawson (1985), Rogerson (1985)
0.018	Mean sediment yield over four-year period from stormflow runoff measured at outlet from three headwater basins all < 4.2 ha.	Miller (1984)
0.036	Mean sediment yield over 3- to 4-year period from stormflow runoff measured at outlet from nine headwater basins all < 4.9 ha.	Miller et al. (1988)

¹Wischmeier and Smith (1978).

minimum, mean, and maximum factor values for forest conditions (Table 2).

The second dataset uses sediment yield rates from small, forested headwater basins within the Ouachita Mountains given in three different studies (Table 2). All three studies used one or more undisturbed basins as experimental controls (Miller 1984; Lawson 1985; Rogerson 1985; Miller et al. 1988) and measured annual sediment yields. None of these studies noted any mass wasting or change in either hillslope or channel sediment storage, but the channel descriptions, in particular, are either lacking or cursory. The shortcomings of using sediment yield to infer erosion rates are well documented (e.g., Trimble 1977; Walling 1983). However, when compared to the USLE estimates, those based on sediment yields seem plausible and provide some additional guidance in judging what a representative forest erosion rate is for the Ouachita Mountains. Furthermore, yields from small low-order basins are less influenced by potential storage and lag effects that complicate erosion vs. stream sediment yield relationships in larger drainage basins.

The estimates range across four orders of magnitude. Those based on annual sediment yields are relatively consistent, and fall between the minimum and mean rates predicted by Dissmeyer and Stump (1978). The maximum USLE prediction is based on the equivalent of worst-case conditions, so it does not seem typical of what occurs over most of the Ouachita Mountains. Based on these values, a rate of 0.20 tonne/ha/yr would seem a reasonable estimate of typical forest erosion rates in the Ouachita Mountains.

STUDY AREA

The WPG Trail Complex study area is in the Ouachita Mountains of western Arkansas (Figure 1) near the town of Mena. The area has a humid subtropical

climate, with hot summers, relatively mild winters, and year-round precipitation. Mean annual precipitation in Mena is about 1,350 mm, is distributed evenly throughout the year, and occurs predominantly as rain. Intense rainfalls (>2.5 cm/day) are common and can occur in any season. In the 12 months preceding our May 2012 field work, the WPG area received 1,613 mm of precipitation which is equivalent to the 56 percentile of the annual precipitation distribution based on the 1981–2010 climate normals (U.S. National Oceanic and Atmospheric Administration, 1981–2010 U.S. Climate Normals. Accessed July 31, 2018, <https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals/1981-2010-normals-data>). Air temperatures were somewhat above average throughout the 2012 winter and early spring.

The Ouachita Mountains consist of generally east–west trending, approximately parallel ridges, with typical peak elevations in the study area of about 423–488 m. The geology is complex, characterized by Paleozoic sedimentary rocks (Figure 1) that have undergone extensive tectonic deformation. The geological formations in the study area represent various combinations of relatively weak and readily weathered shales, hard and highly resistant cherts and novaculites, and sandstones of intermediate and highly variable resistance.

Soils in the study area are predominantly Typic Hapludults on ridgetops and sideslopes, with some Dystrudepts in thin-soil areas. Some Paleudalfs are also found on upland sites. Valley bottom soils are Typic Udifluvents or Ultic Hapludalfs (Olson 2003). Except in valley bottoms, soils are thin, mainly < 1 m over weathered or unweathered bedrock, and rock outcrops are common. Soil rock fragment content is high, with volumes varying from >30% to 70% or more.

The study area is almost entirely forested with a mixture of pines (mainly shortleaf pine, *Pinus echinata*) and hardwoods. The hardwoods include a variety of oaks (*Quercus* spp.), with Sweetgum (*Liquidambar styraciflua*), alders (*Alnus* spp.), and

sycamore (*Platanus occidentalis*) common along the valley bottoms.

No timber harvesting has occurred within the area since 1992. Just over 68% of the study area has been burned since 1992. Controlled burns account for 97% of the area burned, with small wildfires causing the remainder. None of these fires were reported to have produced significant areas of bare soil or erosion. Past research under similar conditions found no substantial change in surface erosion after controlled burning (Swift et al. 1993).

The WPG trail system is composed of county roads; open and closed Forest Service (FS) roads; and open and closed ATV trails. For brevity, we will refer to all routes within the WPG system as "trails," noting that many were originally constructed as roads. For this study, the trail system is that existing at the time of our field work, and documented in USDA Forest Service (2013, WPG Area Trails and Roads: Alternative A map). All references to trail numbers use those listed on this map. At that time, the "active" trail system included 61.6 km of trails that were open year-round, 7.3 km of trails that were open seasonally (February through October), and 8.1 km of trails that were closed but had been open prior to September 2010. A few trail sections (5.0 km) had been restricted to highway-legal vehicle use only since 2001, but prior to that ATV use was allowed. While highway-legal vehicle use is allowed over much of the trail system, ATV use has been predominant since the trail system opened.

Maintenance activities such as trail grading and surface aggregate replacement, which might affect sediment availability and erosion rates, have occurred in the past but detailed information on locations and timing was not available. With the exception of sample section 6b (Figure 2), we observed that none of the other sampled trail sections had been affected by recent maintenance work.

An extensive program of trail improvements was initiated in 2011 to reduce off-trail sediment export and potential sediment impacts to streams (Stinchfield et al. 2011; Poff 2012). These improvements include redesigning sections of the trail system and installing more than 700 sediment traps. Only a small part of these improvements had been implemented before May 2012, but did include sample section 6b.

METHODS

Sampling Overview

Spatial data and aerial photographs were used to evaluate the trail network extent and assign relevant

attributes. Trail transect data were used to determine sediment availability. Data from sediment traps previously installed along a portion of the trail system were used to directly measure eroded sediment volumes. Details are given below.

Field work was conducted over two weeks in May 2012, primarily on trails designated as open at that time. However, sampling included a portion of Trail 243 that was closed to ATV use before 2006, and all vehicle use since 2008. This section provided an opportunity to sample a "recovering" trail that had not been used for several years.

Trail System Characteristics and Measurements

The primary spatial data used were derived from the Roads layer for the entire ONF, and the 10-m digital elevation models (DEMs) for the Board Camp, Eagle Mountain, Mena, and Nichols Mountain quadrangles. All of these data were obtained from the ONF. The Roads layer was used to extract all travel routes within the WPG study area.

WPG trails were subdivided into subsegments. These are defined by a minimum elevation difference of 1 m over a subsegment's length. The terminology and procedures used to derive subsegments are detailed in the Supporting Information. This procedure produces trail subsegments that are consistently defined; long enough that elevation differences between the start and end of each subsegment are real (within the limits of the DEM data); short enough to capture the general slope trend without being overly affected by internal slope variations and so that all other subsegment feature attributes are constant. Attributes assigned to each subsegment are listed in Table 3. Subsegment slope gradient and length are computed from the start and end elevations, and horizontal length.

Construction type was determined using 1992 aerial photographs. Any trail visible on those photographs and occurring on the 2011 trail map is considered as being originally constructed as a road, predating construction of all trails added for ATV use.

The *LS* factor from the USLE (Wischmeier and Smith 1978) was also computed for each subsegment. The USLE is a widely used empirical equation developed to estimate the average erosion rate from the ground surface using factors that represent the physical conditions and management practices present or planned. It is given by

$$A = RKLSCP, \quad (1)$$

where *A* is the erosion rate, *R* is the rainfall and runoff potential, *K* is the soil erodibility, *L* is the slope

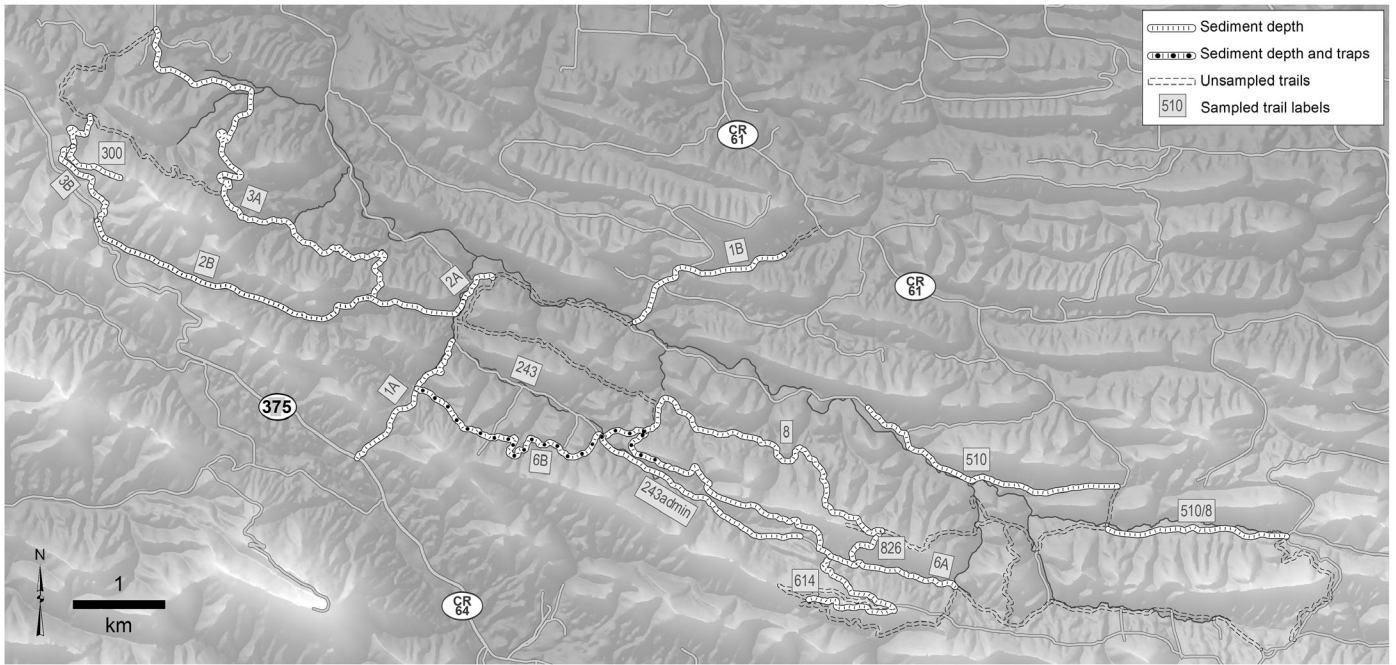


FIGURE 2. Location of sampled trail sections and survey measurements in the WPG Trail Complex.

TABLE 3. Attributes assigned to each trail subsegment in the Trails spatial data layer created for the WPG study area.

Attribute alias	Description
Trail number	Official route number ¹
Subsegment ID	Unique sequential number
Construction type	Indicates whether originally constructed as a roads or as an OHV trails ¹
Trail status	Indicates whether it is part of the designated trail system ¹
Use type	Designated vehicle type restriction (e.g., OHV only, Highway only) ¹
Access status	Indicates trail availability for use (e.g., open, closed) ¹
Sampling type	Type of measurements taken during field work
Start elevation	Elevation at one end of subsegment (m)
End elevation	Elevation at other end of subsegment (m)
Horizontal length	Length (m)

¹Based on official designations taken from the WPG Area Trails and Roads: Alternative A map (USDA Forest Service 2013).

length, S is the slope gradient, C is the ground cover, and P is the conservation practice employed. In applications, the L and S factors are generally combined to produce a "topographic factor" called LS .

For the most part, the R , K , C , and P factors in the USLE are constant over the trail system, thus the LS

factor is the predominant independent variable affecting trail erosion potential and provides a useful metric to assess their combined influence.

The LS value for each subsegment was computed using the equation given in Dissmeyer and Foster (1984: 38):

$$LS = \left(\frac{L}{72.6} \right)^m (65.41 \sin^2 S + 4.56 \sin S + 0.065), \quad (2)$$

where L is the slope length (ft), S is the slope angle (degree), and $m = 0.2$ if $S < 1.0\%$, 0.3 if $1.0\% \leq S < 3.5\%$, 0.4 if $3.5\% \leq S < 5\%$, and 0.5 if $S \geq 5.0\%$.

Sediment Availability Measurement

Sediment availability is determined by the volume of sediment present on the WPG trails. Along any given length, volume is a function of the mean trail width and sediment depth (i.e., thickness). Trail width and sediment depth are determined from cross-trail transect measurements collected over about 40 km of trail (Figure 2). Transects were located approximately every 160 m (measured by pacing). Trail width was measured by tape and included only fully denuded surfaces (i.e., trail shoulders were excluded if they were even partially vegetated). Sediment depth was measured using a ruler at 5–12

points across each transect, depending on depth variability, after lightly scratching or chipping the weathered surface with a rock hammer. Rock clasts > 16 mm were not included in depth measurements. Depths were measured to the nearest cm when ≥ 1 cm, recorded as 0 when no sediment occurred, and <1 cm when between 0 and 1 cm. The <1-cm protocol was used when sediment was clearly evident but depths were difficult to measure with greater precision. In addition, one or more gravel-size clasts were inspected at each transect to determine the rock types comprising the trail sediment.

Erosion Rate Estimation

Erosion rates were estimated using two different methods. The first uses the sediment volumes captured within sediment traps to compute erosion rates. The second assumes that the current sediment volume measured on the trails is all removed each year and is therefore equivalent to the annual erosion rate.

Thirty sediment traps along Trail 6 (Figure 2) were sampled to determine the rate of sediment removal from the trail surface over a known time period. Every third sediment trap was examined along the 4.4 km of trail. The sampled traps were among the first constructed. They were not installed for the purposes of this study; rather we took advantage of their availability.

Each trap was constructed immediately beside a trail section at the downslope end of a dip built across the trail to route all runoff into the trap. The sampled traps were constructed during two different time periods: about 12 and 6 months prior to sampling. The traps were constructed as simple unlined pits, roughly rectangular, with near vertical sides and a flat bottom. Sediment excavated during construction was spread back onto the trail surface and compacted (Stinchfield et al. 2011).

Trap sediment volume was measured by probing with a shovel blade or steel rod. The trapped sediment was easily distinguished from the base of the pits, which were excavated into tight clayey B- or C-horizons or into weathered or intact bedrock. Generally nine depth measurements per trap were made (with more for a few larger traps) by grid sampling. Surface area length and width were measured by tape and combined with mean depth to calculate the volume. Both the total trap volume and the volume occupied by sediment were measured. Bulk density samples were taken from six sampled traps, averaged, and used with sediment volume to compute sediment mass. The relief and contributing area of the trail surface for each trap was determined by field survey using a handheld laser level, prism rod, and tape.

The annual erosion rate based on trap measurements is computed from

$$E = \frac{V\rho}{At}, \quad (3)$$

where E is the erosion rate (tonne/ha/yr), V is the mean volume of trapped sediment (m^3), ρ is the sediment bulk density (tonne/m^3), A is the contributing trail area supplying the sediment (ha), and t is the time period over which the erosion occurred (year).

The second method uses available sediment volume to estimate the annual trail erosion rate. The annual erosion rate is calculated from trail sediment depths by:

$$E = \frac{d\rho}{t}C, \quad (4)$$

where d is the mean sediment depth (m) for all transects within a given trail section, and $C = 10,000 \text{ m}^2/\text{ha}$ (a conversion constant). Equation (4) is equivalent to Equation (3) but here V is computed from

$$V = wLd, \quad (5)$$

where w is the mean width (m) of all transects, and L is the total length (m) of the given trail section. A from Equation (3) is given by

$$A = wL. \quad (6)$$

Substituting Equations (5 and 6) into Equation (3) and simplifying yields Equation (4). The bulk density for trail sediment is estimated as $1.5 \text{ tonne}/\text{m}^3$ based on the range of $1.4\text{--}1.6 \text{ tonne}/\text{m}^3$ for volume-weight values for both aerated sand and gravel sediment (SCS 1983).

The second method is based on the assumption that sufficient runoff energy will occur during the next 12 months to erode all of the trail sediment observed at any given time. The veracity of this assumption is addressed in the Discussion section.

Sample Representativeness

The transect sampling was done over 38.4 of the 77.0 km (~50%) of the active trail system. This high proportion, along with sample lengths being distributed throughout the entire trail system (Figure 2), makes us confident that results are representative. In contrast, the sediment trap sampling was an opportunity sample over a much shorter length of the system (4.4 km or 5.7%).

The *LS* factor is used to assess how representative the sediment trap sample is of the entire trail system. Trail subsegments are classified into three groups for analysis: (1) those having sampled sediment traps; (2) all those having sediment traps, sampled or not; and (3) all subsegments.

Statistical comparison of *LS* values indicates that the erosion potential for the Sampled-Traps group is lower than that for the All-Subsegments, and All-Traps groups. Median values and sample sizes of slope length, gradient, and *LS* are listed in Table 4. The Kolmogorov–Smirnov and Anderson–Darling nonparametric tests were used to assess how representative the *LS* values for the two trap groups are of the population *LS* values for the trail system. Both are used because the Kolmogorov–Smirnov is more sensitive to differences near the distribution center, whereas the Anderson–Darling is more sensitive to differences at the distribution tails. As multiple comparisons are involved using both tests, the Holm (1979) *p*-adjustment is used here and for all other multiple comparison tests to maintain an overall alpha level = 0.05. Both methods indicate that the All-Traps and Sampled-Traps groups differ from the All-Subsegments population (all $p < 0.009$), but differ as to whether the All-Traps and Sampled-Traps groups are different. The Anderson–Darling test indicates that they are ($p = 0.044$), whereas the Kolmogorov–Smirnov test indicates that they are not ($p = 0.138$). The results indicate that the two groups are essentially not different around their distribution centers, but differ in their extreme values).

Differences between groups in slope gradient explain the differences in *LS* values. Slope medians differ such that All-Subsegments > All-Traps > Sampled-Traps slopes, the same ordering as for *LS* values. Group slope lengths have the opposite ordering, indicating that slope length has little effect on *LS* factor differences.

Analysis indicates the sampled sediment traps occur on subsegments having lower erosion potential than that which is representative of the all trail subsegments, or possibly even all subsegments with traps. Thus, erosion rates based on the sampled traps likely provide a low or conservative estimate of overall rates within the trail system.

RESULTS

Trail Dimensions

Slope gradients along WPG trails range from 0.0% to 69% with a median slope of 8.9%. Seventy-five percent of slopes are <15%, and only 10% are >22%. The slope lengths for trail subsegments over which gradients were computed range from <1.0 to 279 m, with a median length of 21.2 m and 80% of lengths being between 8.6 and 66.0 m. The denuded width of trails based on transect measurements varies from 1.60 to 14.8 m, with a median width of 2.50 m.

The trail surfaces are covered by a thin, discontinuous layer of sediment and frequent exposures of bedrock (Figure 3). For all trails, the mean transect sediment depth is <1.0 cm, which is also the minimum measureable depth used in this study. Eighty-six percent of all transects had mean depths <1.0 cm with a maximum mean depth of 5.2 cm.

The trail sediment consists of or is derived from chert, novaculite, shale, sandstone, and quartz rock types. Shale is notable in that it is much less resistant to breakage and weathering than the other rock types observed, yet is common due to its widespread presence in underlying formations. These rock types are highly intermixed along the trails, reflecting both the high spatial variability in local bedrock types underlying the trails and additions of road aggregate from local quarries during trail maintenance.

Differences in Sediment Availability

Initial data inspection suggests that trail widths may vary within the trail system. Four "condition types" were identified based on initial data analysis and used to group trail sections according to possible differences in width (Figure 4). Each type is labelled using the characteristic most common among its member trail sections and defined in Table 5. The Kruskal–Wallis test indicates that at least one condition type differs in width from the others ($p < 0.001$). Pairwise multiple comparisons using the Dunn test show that trail widths clearly differ

TABLE 4. Sample sizes and median values for slope gradient, slope length, and *LS* factor¹ for WPG trail subsegments.

Subsegment group	Sample size	Slope gradient (%)	Slope length (m)	<i>LS</i> factor
All subsegments	2,454	8.9	21.2	0.91
All subsegments with sediment traps	559	6.8	26.4	0.71
All subsegments with sampled sediment traps	30	4.6	35.8	0.51

¹*LS* factor is the combined Length and Slope factors in the USLE (Wischmeier and Smith 1978).



FIGURE 3. Examples of trail surface and sediment cover along WPG trails: (a) ponding and fine-sediment accumulation along low-gradient section; (b) bedrock outcrops and surface aggregate displacement along higher gradient section; and (c) rill formation and aggregate displacement along intermediate gradient section.

between the Trail 1B type and all other types (all $p < 0.001$), and that the Other Roads type differs from the All Trails type ($p < 0.001$). The testing also indicates that the All Trails and Recovered Road types do not differ ($p = 0.102$). The difference between the Other Roads and Recovered Road is uncertain ($p = 0.047$). When widths for the All Trails and Recovered Road types are combined and the groups retested, the Trail 1B, Other Roads, and All Trails + Recovered Road types all clearly differ from each other (all $p < 0.001$). Both median and mean widths for all types are listed in Table 6. Nonparametric tests are used because the data distributions and sampling methods do not meet the assumptions of parametric analysis of variance methods.

Assessing sediment depth differences between trail condition types is complicated by the fact that a very high proportion of the depths was < 1.0 cm, the minimum measurement limit used. Therefore, to statistically test differences between trail condition types, the proportion of depths < 1.0 cm are used.

Sediment depths in the Recovered Road type markedly differ for those in the other three condition types. An overall chi-squared test of proportions confirms that differences in sediment depths exist between the four groups ($p < 0.001$). The difference between the Recovered Road type and the other three types is so obvious as to not require statistical testing (Figure 5). Also, the equivalence of depths for transects in the Trail 1B and All Trails groups seems clear, thus the only comparison in question is

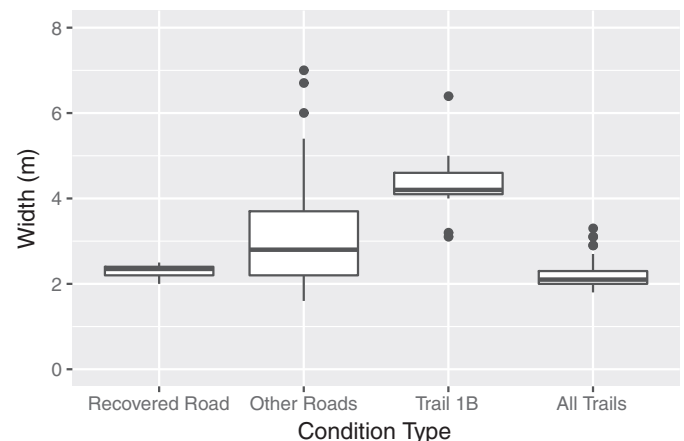


FIGURE 4. Width differences for WPG trail condition types. Log-10 scale is used to better display data distributions within groups. Width scale limit is set to better display data distributions. Limit excludes maximum values of 12.5 and 14.8 m for the Other Roads and All Trails types, respectively.

between the Other Roads and the combined Trail 1B and All Trails group. A pairwise test of these two groupings yields $p = 0.07$ (or 0.10 if the Yates continuity correction is used). While not conclusive, this result does suggest that sediment depths may be greater for trail sections within the Other Roads condition type.

Differences in erosion potential between condition types are evident (Figure 6). An overall Kruskal–Wallis test of LS values ($p < 0.001$), followed by Dunn

TABLE 5. WPG trail condition types based on differences in construction type and trail status as of May 2012.

Condition type	Description
Recovered road	Continuous portion of Trail 243 that was closed to All Terrain Vehicle use sometime prior to 2006 and to all but administrative use in 2008
Trail 1B	Continuous portion of Trail 1 constructed as a road but with apparently larger widths
Other roads	All other trails originally constructed as roads
All trails	All open or recently closed trails constructed as trails

multiple comparison tests, yield extremely low p -values ($p < 0.001$) for all comparisons except between the Trail 1B and Other Roads types ($p = 0.270$).

However, differences in erosion potential do not consistently explain differences in trail widths and sediment depths between condition types. If trail sections with greater erosion potential experience greater erosion, and greater erosion produces either wider trails or shallower sediment depths, then the condition types with higher LS values should have wider trails or shallower sediment depths, and vice versa. Table 7 tries to clarify the relationship between LS values and the two factors which determine sediment availability. Erosion potential does align with sediment depth differences, in that the three types with higher LS values (Trail 1B, Other Roads, and All Trails) all have the shallowest sediment depths, and the type with the lowest LS values (Recovered Road) has the greatest depths. However, the correspondence between erosion potential and trail width differences is not consistent. The All Trails type has the highest LS value but is one of the two types with the narrowest widths. The Trail 1B and Other Roads types both have LS values less than the All Trails type, but have trail widths greater than the All Trails type. Erosion potential corresponds best with the Recovered Road conditions as this type has lowest LS values, narrowest widths, and greatest depths.

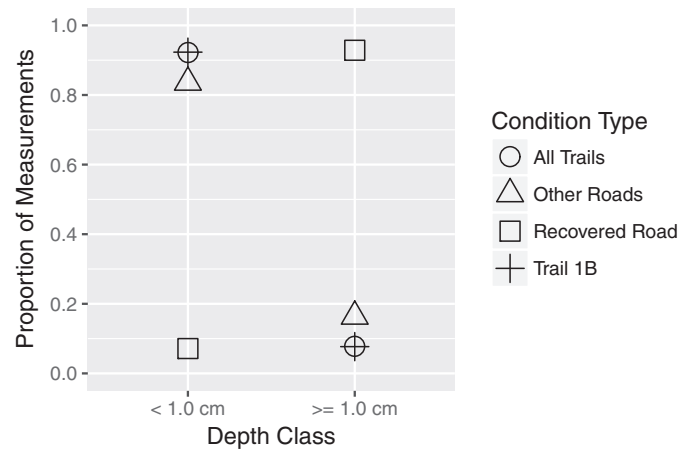


FIGURE 5. Sediment depth differences for WPG trail condition types.

The differences in LS values between condition types are largely driven by differences in slope (Figure 6a). The relative ordering of condition types by slope medians is the same as that for LS factors: All Trails > Other Roads and Trail 1B > Recovered Road. Differences in slope length between condition types appear to have little effect on their respective LS values.

Erosion Rates from Sediment Trap Sampling

The mean sediment volume captured in the 30 sampled traps was 0.85 m^3 (Table 8). The material in the traps was predominantly composed of unconsolidated sediment from the trail surface and some organic matter (mostly leaves and pine needles), and had a mean bulk density of 1.26 tonne/m^3 . Actual amounts of trail sediment removed since trap construction are likely to be greater than the volume of trapped sediment. Traps are unlikely to trap all sediment removed from their trail catchment areas. At most of the traps, rills were newly cut into the constructed berms on the downhill side of the traps and traceable sediment was deposited on the forest slopes

TABLE 6. Denuded widths and sediment depths for different trail condition types within the WPG Trail Complex.

Condition type	Construction type	2012 access status	Median/mean width (m)	Median/mean depth (cm)	Total length (km) ¹
Recovered Road	Road	Closed	2.20/2.38 ²	1.96/2.13	2.56
Trail 1B	Road	Open	4.20/4.32	<1.0/0.5 ³	2.06
Other Roads	Road	Open	2.80/3.13	<1.0/0.5 ³	56.3
All Trails	Trail	Open or recently closed	2.20/2.38 ²	<1.0/0.5 ³	18.6

¹Lengths are based on total mapped (not sampled) distances as of May 2012.

²Widths in these two types do not differ ($p = 0.10$), thus the widths listed for both are those computed using all cross sections within these two groups.

³Differences in depths between the indicated condition types could not be reliably tested due to the high percentage of censored measurements within the groups. See the text for the rationale used to estimate the listed mean depth for the combined group.

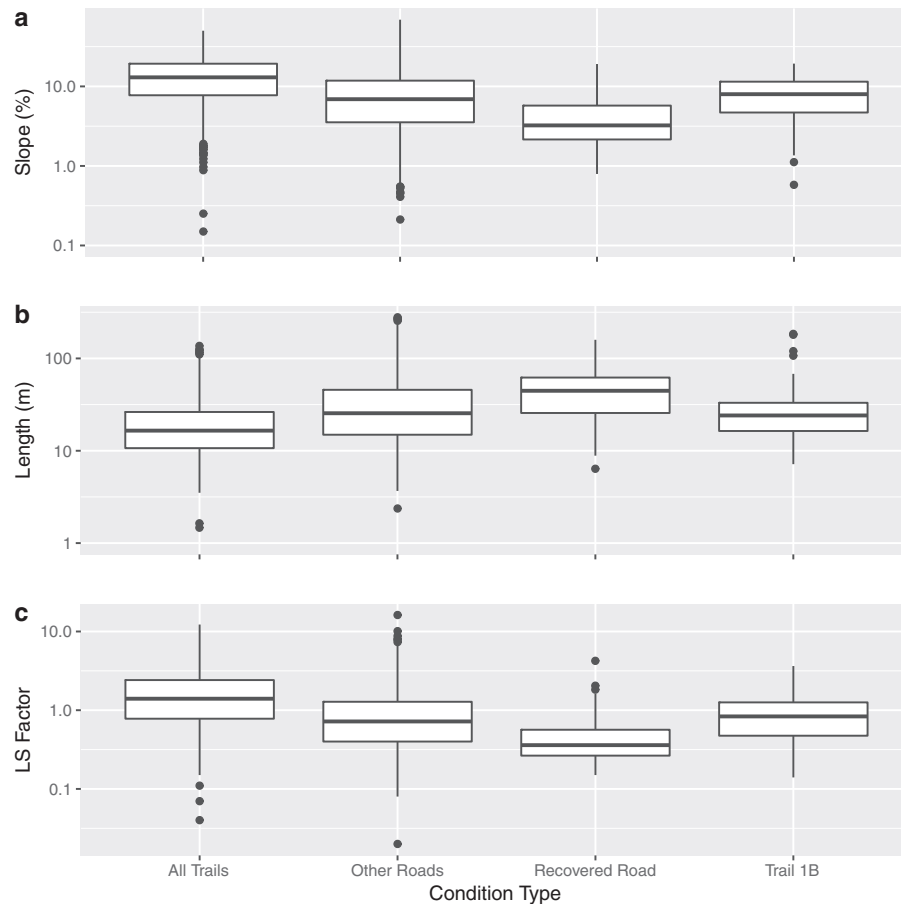


FIGURE 6. (a) Slope gradient, (b) slope length, and (c) *LS* factor values for WPG trail subsegments by condition type. Log-10 scales are used and limits set to better display data distributions within groups. Scale limits exclude minimum slope values of 0.04% and 0.08% for the Other Roads and All Trails types, respectively, and minimum length value of 0.009 m for the Other Roads type.

TABLE 7. Relative rankings of transect width, sediment depth, and *LS* factor values by condition types found in the WPG trail system. The *LS* factor is the combined slope gradient and slope length factors from the USLE (Wischmeier and Smith 1978).

Condition type	Trail width	Sediment depth	<i>LS</i> factor value
Trail 1B	1	1	2
Other roads	2	1	2
All trails	3	1	1
Recovered road	3	2	3

Note: Rankings are from the largest to the smallest value for trail width and *LS* factor value, and smallest to largest for sediment depth. The rankings for width and depth reflect the expected effect of the *LS* factor (i.e., a larger *LS* factor value would cause a larger trail width and smaller sediment depth). Different ranks indicate which condition types statistically differ for a given variable ($\alpha = 0.05$).

below clearly indicating that some trail sediment was bypassing the traps.

The mean trap erosion rate is 210 tonne/ha/yr and ranges from 43 to 740 tonne/ha/yr. Erosion rates are

TABLE 8. Summary statistics for deposition in 30 sediment traps on Trail 6 in the WPG Trail Complex.

	Mean	Standard deviation	Maximum	Minimum
Captured sediment volume (m ³)	0.85	0.49	2.02	0.17
Trap volume (m ³)	2.56	1.55	6.47	0.51
Sediment/trap volume (percent)	38	15	69	8
Trail contributing area (m ²)	87.9	56.9	335.9	23.9
Maximum relief (m)	3.21	2.04	10.36	0.53
Sediment volume/contributing area (m ³ /m ² /100 = cm)	1.2	0.8	3.2	0.2

not statistically different between older and younger traps (Mann–Whitney test, $p = 0.84$), although rates for the younger traps do show greater variability (Figure 7).

The relief of the upslope trail segment, trap age (i.e., length of the sediment collection period), and trap volume were all examined to determine their effect on trail erosion rates. Trap volume was included because the physical space on the downslope side of the trail generally determines the trap volume, not the expected erosion amounts; thus sediment capture may be affected by trap size. That trap volume could have limited sediment capture was also suggested by the aforementioned newly cut rills and fresh sediment deposition downslope. Linear model analysis was used to identify which model factors and factor interactions were significant, and to fit trend models. Linear, $\log(x)$, quadratic, and nonlinear ($y = b_1e^{b_2x} + b_0$) models were all examined to select the best one based on model p values and explained variance.

Results indicate strikingly different relationships between erosion rates and trail relief, depending on trap age. In contrast, the relationship with trap volume does not vary with trap age. The relationships between erosion rate, trail relief, and trap volume by

the two trap age classes are shown in Figure 7. For the older traps (collection period = one year), the linear regression model is given by

$$E = 91.52 + 32.96h, \quad (7)$$

where h is the trail relief (m) and V is the trap volume (m^3). This model is significant ($R^2 = 0.39$, $p = 0.017$) and fits the data well with no apparent outliers, high leverage cases, or indications of multicollinearity. The quadratic model was also significant and explained a bit more variance ($p = 0.039$, $R^2 = 0.45$), but with a sample of only 15, we think it is hard to make the case that this model is superior to the simpler linear one. As expected, trail relief varies directly with erosion rate.

In contrast, erosion rates for the younger traps (collection period = 3–6 months) exhibit an anomalous inverse relationship with trail relief (Figure 7a). The $\log(\text{relief})$ model had the lowest p -value (0.073) and the second highest R^2 value (0.21) of the models tested

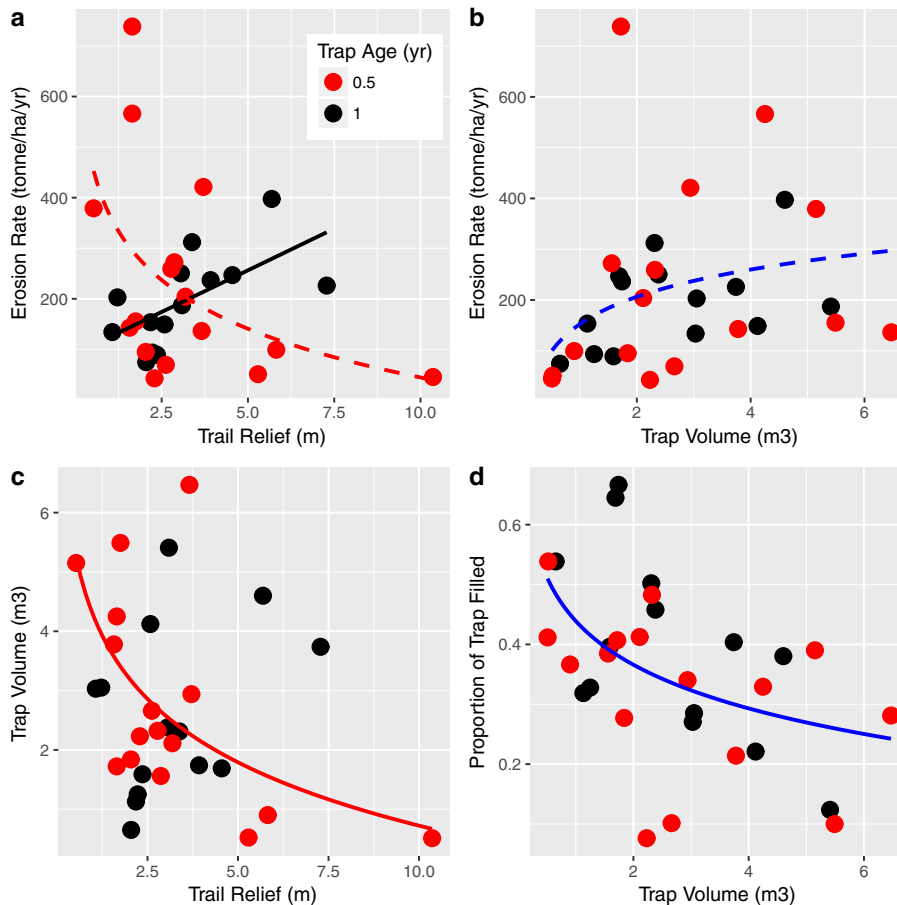


FIGURE 7. Relationships between sediment trap erosion rate with trail relief (a) and trap volume (b); and trap volume with trail relief (c) and proportion of trap volume filled (d) as affected by trap age for sampled traps in the WPG Trail Complex. Lines represent trend model by age group where line type indicates model significance (solid = $p < 0.05$; dashed = $0.05 \leq p < 0.10$). Blue lines are used when age does not significantly affect the given relationship and all data are combined for modeling.

$$E = 364.45 - 138.97 \log h, \quad (8)$$

While the model p -value is >0.05 and only explains 21% of erosion rate variability, it does appear to capture the general trend in the data. As with the older traps, neither volume nor the relief $\times$ volume interaction factors are significant (all $p > 0.52$). The extreme values for relief, volume, and erosion rate for all sample sites all occur within the younger trap group.

There is no obvious explanation for the inverse trend. It is not the result of a few high leverage cases as removal of the four cases with the highest model leverage neither improves the quality of fit nor reverses the trend direction for trail relief. The relationship between trail relief and trap volume also differs by age class in that volume varies inversely with relief with the younger traps ($p = 0.029$) (Figure 7c), but relief has no significant effect on volume with the older traps ($p = 0.242$). If younger, high relief, low volume traps were overfilling, then computed erosion rates for those traps would be too low. While the proportion of filling does show an inverse trend with trap volume for both age classes ($p = 0.006$), only one of the younger traps exceeded 50% of trap volume whereas four of the older traps did (Figure 7d). Also, volume does not appear to affect erosion rates for either the older or younger traps after the effect of relief is accounted for (all $p > 0.314$). Moreover, except for one trap, the range of relief and volume values between the two age classes is very similar (Figure 7c). Based on trail relief, trap volume, and proportion of trap filling, there are no important differences between the younger and older traps other than the duration of the sediment collection periods. And, despite the differences with trail relief noted above, there is no compelling evidence that erosion rates for the younger traps are less accurate and should be ignored. Therefore, the data for all traps were combined for computing a mean erosion rate.

Erosion Rates from Transect Data

As demonstrated above, sediment depths differ between the trail section within the Recovered Road condition type and the three other trail condition types. The Regression on Order Statistics (ROS) method (Helsel and Cohn 1988; Lee and Helsel 2005) can be used to estimate the mean and other statistics using censored data such as these; however, in cases where the proportion of censored data are $>80\%$, estimates are considered "tenuous" (Lee and Helsel 2005). Mean sediment depths estimated using the ROS method for both trail groupings are listed in

Table 6. The proportion of depth measurements <1.0 cm for the three combined types is 86%. While this value is above the recommended limit, what is certain is that the mean is <1.0 cm. Even if one assumes that all censored transect depths equal 0.90 cm — a highly unlikely event — the mean depth would be 0.98 cm. Using the ROS method produces a more conservative — and probably more realistic — estimate of 0.5 cm for the mean sediment thickness along all open trails, and allows available sediment volumes to be computed.

Differences in available sediment volume on the trails are explained by differences in trail width and sediment depth. Using the data in Table 6, the sediment volume occurring on the Recovered Road trail section is estimated to be $51 \text{ m}^3/\text{km}$ of trail, while that for trails in all other condition types varies from 12 to $22 \text{ m}^3/\text{km}$. The higher volume for the Recovered Road condition is due to the much greater sediment depth along this trail section. The differences between the other three condition types are due entirely to differences in trail width.

Using Equation (4), the annual erosion rate is estimated to be 75 tonne/ha/yr along the active trail system. This estimate is based on the assumption that all fine sediment is removed annually (discussed below). This estimate does not include erosion from the Recovered Road trail section, which was not part of the trail system in 2012. Moreover, the greater sediment depth and other visual evidence along this trail section suggest that sediment is accumulating over time.

Figure 8 shows the relationship between available sediment on the trail area (based on contributing trail length, width, and the mean thickness of available sediment on trails) and sediment collected in the sampled traps on Trail 6. Three key points are evident. First, in all but two cases, sediment collected in traps exceeds that available on trails, typically by about 1.5 times. This underscores our contention that the annual erosion rate estimated above is conservative. Second, while the linear model slope (Figure 8) is significant ($p = 0.03$), there is not a strong relationship between the two variables ($R^2 = 0.17$). Linear, exponential, logarithmic, and quadratic trends were fit to all data, and to the older and younger traps separately. None produced a coefficient of determination greater than about 0.30. Finally, other than the two relatively underfilled traps, there are no apparent differences between the older vs. younger sediment traps.

Trapped sediment volume was also compared to the LS factor for each trap's contributing area, but this revealed no significant relationships or evident trends. No regression model of separate older/newer traps or the entire dataset produced an $R^2 > 0.23$.

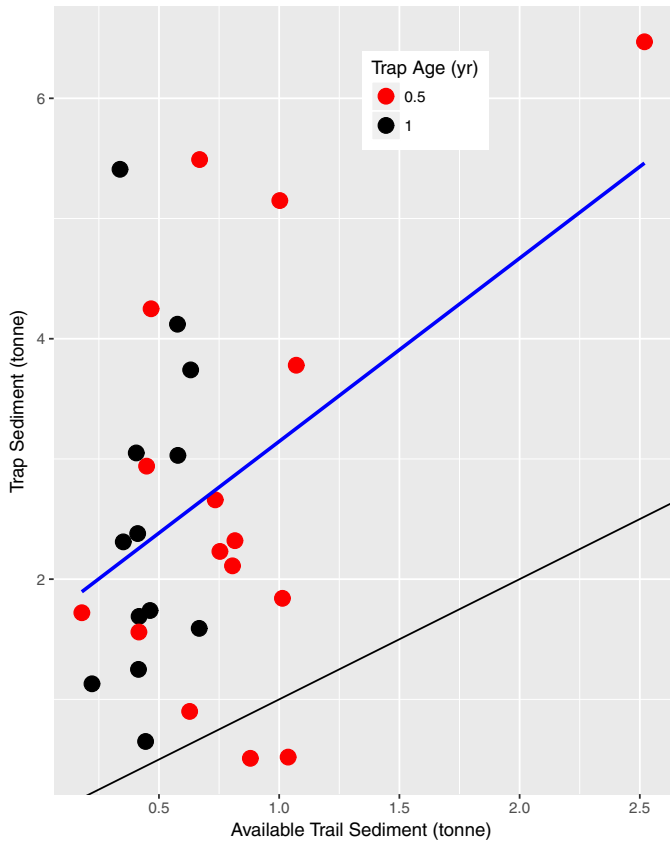


FIGURE 8. Relationship between available sediment on the trail (based on contributing trail length, width, and the mean sediment thickness on all trails) and sediment collected in the sampled traps on Trail 6. The blue line shows the linear trend ($p = 0.03$) for all traps, and the black line shows where trail sediment equals trap sediment.

DISCUSSION

Sediment Availability Differences

Trail width is important because it affects the bare area exposed to erosion. Differences in trail width (Table 6) primarily determine how sediment availability varies within the active trail system. Testing indicates that sediment depths are similar between the three condition types occurring on these trails, whereas widths differ between all three (Table 6).

Construction type (i.e., road or trail) would seem to be more consistent than erosion potential in explaining variations in sediment availability within the active trail system. Trail sections in the All Trails condition type have narrower widths than those in the Other Roads and Trail 1B type despite having larger *LS* values (Figures 4 and 6). A width difference between construction types is not too surprising given that logging roads are constructed to pass wider vehicles, provide more frequent two-way traffic

passage, and have thicker beds to support heavier vehicles.

However, the width difference is noteworthy for two reasons. First, as just the denuded width was measured, not the original constructed width, this result indicates that OHV use continues to affect a predominant portion of the constructed width on trails originally built as roads. Second, it is common practice on FS lands to repurpose existing roads as OHV trails. For the WPG trail network, roads account for 76% of the network by length and an even greater percentage by surface area. Wider trails increase sediment availability and thereby allow for higher erosion rates.

The Trail 1B section is unusual in that its mean width is more than 1 m greater than that for the Other Roads type (Table 6). As noted above, the erosion potential for the Trail 1B type does not differ from that for the Other Roads type. The Trail 1B section traverses slopes with soils that have predominantly Slight to Moderate erosion hazard ratings (Olson 2003), which is very similar to trail sections in the Other Roads type. It is possible that all or part of the Trail 1B section was originally constructed using different standards, or past maintenance may have widened it over time (Bubba Brewster, ONF, 2018, personal communication). Whatever the reason, the Trail 1B trail section has the largest sediment availability ($22 \text{ m}^3/\text{km}$) of the three condition types that comprise the active trail system because it is the widest.

Erosion Rates

The erosion rate produced using observed trail sediment availability is based on the assumption that sufficient runoff energy occurs during the next 12 months to erode all of the trail sediment observed at the time of sampling. This assumption is well supported by the results. Though the sediment trap measurements were taken along a much smaller portion of the trail network, the mean erosion rate of 210 tonne/ha/yr from sediment traps clearly indicates that sufficient energy occurred in the previous 12 months to erode the estimated 75 tonne/ha of available sediment measured on the trails. This 12-month period received precipitation amounts that were quite typical for the area. The analysis of sample representativeness indicates that, if anything, the erosion measured by the sampled traps may be lower than that occurring on average over the entire trail system because the trail subsegments adjacent to the sampled traps have lower erosion potentials. With the exception of the Recovered Road trail section, there is no evidence of increased sediment storage

over time on the trails, as sediment depth is very similar and very thin (<1 cm) on all sampled trails. It seems more likely that the erosion rate derived using a one-time sampling of sediment depths is low given that it does not include all of the sediment produced over an entire year. The direct comparison of available sediment on the trails and sediment volume in traps (Figure 8) supports this interpretation.

The mean sediment depth estimated for the active trail system (0.5 cm) is similar to the annual soil production rate previously estimated for bare rock surfaces in the Ouachita Mountains. Phillips et al. (2008) determined that the soil production rate for recently exposed bedrock surfaces of similar lithology in the Ouachita Mountains was 0.5–1.0 cm/yr. That the observed mean sediment depth is at the lower end of this range may be due to tree root growth being an important factor affecting the production rate determined by Phillips et al. (2008), and trees being absent on the WPG trails. However, OHV use on the trails could at least partially compensate for the lack of trees in affecting soil production. This is due to the disturbance effects of traffic, as indicated by the obvious dislodging and sorting of rock fragments (Figure 3). Perhaps more likely is that the mean sediment depth corresponds to the lower end of the range because measured trail sediment represents less than a full year of sediment production, as noted previously.

We fully recognize that erosion occurs as an episodic and spatially discontinuous process on the trails. At any given time, there will be sediment patches on trail surfaces that can remain in storage for more than one year. It is also true that there can be sediment patches that will accumulate and erode multiple times during a single year. Because our argument above is based on representative characteristics of sediment availability on the trails as a whole, we think it accounts for such variations over time and space.

Together, the sediment availability observed on the trails and the sediment amounts measured in the traps allow the current trail erosion rate to be bracketed between 75 and 210 tonne/ha/yr. The lower rate of 75 tonne/ha/yr provides a plausible estimate where sediment availability is determined by weathering and trail use only. The rate of 210 tonne/ha/yr provides an estimate where sediment may be more available (e.g., when excavated sediment is spread back onto the trail upslope of the traps).

However, there are reasons to think that both estimates are conservative. As noted earlier, the lower estimate may not include all sediment produced over an entire year. The higher estimate based on the sampled sediment traps did not include all of the sediment eroded from the adjacent trail area. Moreover, the fact that trail subsegments adjacent to the sampled traps have lower erosion potential than what is

typical for the entire trail system suggests that higher erosion rates are quite possible.

We speculate that differences in sediment supply over the duration of the two collection periods for the sediment traps may explain the anomalous relationship between erosion rate and trail relief for the younger traps. Sediment supply is the only factor unaccounted for in our analysis of factors affecting trap sediment capture. Sediment production from trail use and weathering occurs throughout most of the year, as does rain generated runoff on the trails. Increased sediment availability during an additional six months might change erosion amounts sufficiently at the younger traps with higher relief to reverse the apparent inverse relationship with relief. Additional monitoring of the sediment traps would be needed to test this idea.

The lower erosion rate estimate for the trails of 75 tonne/ha/yr is within the range of rates measured in past studies of surface erosion from unpaved logging roads in the Ouachita Mountains, while the upper estimate of 210 tonne/ha/yr is much greater (Table 1). Precipitation during these prior studies was 143% and 5%, respectively, above mean annual amounts (Miller et al. 1985; Vowell 1985), suggesting that the mean rates in both studies might be similar to or even higher than rates occurring under more typical conditions. A Virginia Piedmont study (Brown et al. 2013) reports rates for bare road surfaces whose range includes and is larger than the range reported here (Table 1). It is important to note that the WPG rate is occurring on trails that are largely cut down to bedrock whereas the cited studies used road segments that were either relatively new (Vowell 1985), recently regraded and resurfaced (Brown et al. 2013), or subjected to very high precipitation amounts (Miller et al. 1985).

The source of the sediment observed on the trails must be predominantly from erosion within the trail prism rather than being supplied by the forest area bordering the trails. While downhill movement of sediment eroded from adjoining forest slopes into the trail prism must occur where trails cut into these slopes or across drainage ways, the amount of sediment added is trivial. The rate estimates provided in Table 1 suggest that forest areas would contribute approximately 0.20 tonne/ha/yr to the trails, whereas the annual trail erosion rate is 75–210 tonne/ha/yr, or 375 to over 1,000 times the forest production rate. This means that almost all of the trail sediment must be generated from erosion processes occurring on the trails and not from forest inputs.

Management Considerations

The high soil loss rates compared to minimally disturbed forest and to some past studies of unpaved forest

road and trail erosion suggest that the erosion and sediment impacts of ATV trails warrant further attention. While past impacts on WPG streams have already been identified as a significant management concern (USDA Forest Service 2013; Marion et al. 2014), the fate of sediment removed from trails is largely unknown. We are investigating this question in our current work.

The results suggest that excluding all vehicle access for several years may reduce trail erosion. Despite being originally constructed as a road, trail width on the Recovered Road trail section is significantly narrower than all other trails built as roads (Table 6), indicating that the trail affected area is decreasing over time. In addition, soil depths are significantly greater (Table 4), indicating that erosion is diminished compared to trails with active OHV use. However, this apparent recovery has occurred where erosion potential is very low (Figure 6), which likely reinforces sediment accumulation and vegetation regrowth. This finding is also tentative because the only portion of the trail system that had been closed for more than two years was this one low-gradient section. That said, reconnaissance of a steeper trail section more recently closed revealed no active erosion features and rapid vegetation recovery. Thus trail closure as a passive restoration practice deserves further attention.

The sampled sediment traps along the reconstructed section of Trail 6 are instructive in terms of trap effectiveness and future maintenance needs. Erosion features such as rills, gullies, and washouts along the trail surface were rare compared to other trails. The amount of trapped sediment proves the traps are working, but also indicates the need for regular maintenance. The traps were, on average, 38% full after less than one year. Based on the observed mean sediment capture and mean trap volume (Table 8), the traps would have to be excavated every 1.0–1.5 years to prevent sediment volumes from exceeding 33% to 50% of the trap capacity (an assumed range that would maintain trap efficiency). If one assumes that trail erosion reduces to the 75 tonne/ha/yr rate in later years, then the traps would still have to be excavated every 1.4–2.2 years (assuming the same trap efficiency range and a 25% reduction in eroded sediment volume when captured in the trap). Therefore frequent monitoring and maintenance will be required to maintain their effectiveness.

CONCLUSIONS

Trail width and sediment depth characteristics determine the volume of sediment available along the WPG trail system. The four condition types defined for this study differentiate portions of the trail

system that have significantly different width and sediment depth characteristics. The trail section within the Recovered Road type has greater sediment depth than that found for trail sections in the three types comprising the active trail system (Trail 1B, Other Roads, and All Trails), all of which do not differ in sediment depth. In contrast, trail segments within those three types all differ in width, whereas the widths for the Recovered Road and All Trails types do not differ. Thus the condition types delineate trail areas having different sediment availability.

Construction method appears to influence trail sediment availability more than erosion potential. Among active trails, those originally constructed as roads (the Trail 1B and Other Roads types) have lower erosion potential but greater sediment availability than those originally constructed as trails due to their greater widths.

The annual erosion rate on the trails is estimated to be 75–210 tonne/ha/yr. This range is based on using two independent methods to estimate the erosion rate: trail sediment availability and sediment trap capture. Several reasons are presented to suggest that these estimates may be conservative and that erosion rates may be higher. The low end of the estimated range is comparable to erosion rates determined in past studies of unpaved roads in the Ouachita Mountains (Miller et al. 1985; Vowell 1985), while the high end is much greater. Despite the WPG trails being predominantly cut down to bedrock, there are no indications that erosion has ceased or decreased to negligible rates.

Current trail erosion rates are 375 to over 1,000 times the estimated forest erosion rate of 0.20 tonne/ha/yr, clearly indicating that the source of trail sediment is the trails themselves and not contributions from upslope forest areas. Measured erosion rates and sediment trap observations indicate that frequent trap cleanout will be necessary to maintain continued sediment capture from ATV trails. However, results also suggest that trail closure may be an effective passive reduction strategy.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Trail subsegment delineation procedure.

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