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ARTICLE

Fine sediment storage in an eroding forest trail system

Jonathan D. Phillips[a], Daniel A. Marion[a,b] and Kathleen G. Kilcoyne[a]

[a]Earth Surface Systems Program, Department of Geography, University of Kentucky, Lexington, KY, USA; [b]Formerly: Southern Research Station, USDA Forest Service, Hot Springs, AR, USA

ABSTRACT

We measured fine sediment accumulations (FSA) adjacent to eroding off-highway vehicle trails in Ouachita National Forest, Arkansas. Measured trailside FSA was 643 $m^{3.}$ Extrapolated to the entire trail network, this amounts to 216 t ha^{-1} of trail surface, with a residence time of <1 yr. Natural topographic features are the main storage sites, accounting for 83% of the total, and constructed features for 16%. More than two thirds occur in channels indicates high sediment connectivity. For all types of FSAs, the single largest deposit accounted for about 30% or more of the total. These hotspots are found where topographically suitable storage sites occur downslope of an area of above-average rates of, or recent, trail erosion. Because in many cases trail erosion occurs without evident gullies or rills, these accumulation foci are effective ways to identify erosion hotspots. Relatively small amounts of fine sediment are stored in low-order stream channels. However, the low storage amounts (4,060 m^3 estimated for all low-order streams) and lack of silt and clay indicate that fine sediments are highly mobile once reaching streams. Overall, results indicate predominantly short-term storage of fine sediments and high connectivity with and rapid movement through the fluvial system.

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Introduction

Accelerated soil erosion (i.e. greater than background levels) is associated with both onsite impacts such as land degradation and reduced biological productivity, and offsite impacts such as stream sedimentation and water pollution. Linking offsite impacts with erosion sources can be quite difficult, given that there is rarely a steady-state relationship between soil loss on uplands and sediment supplied to streams (James, 2018). Between erosion source areas and stream channels (and within channels), there may be numerous sites where sediment is stored for various amounts of time. The purpose of this study is to document the fate of fine sediment eroded from an off-highway vehicle trail system (Wolf Pen Gap Trail Complex, Ouachita National Forest, Arkansas). Studies of trail erosion and its geomorphic impacts on streams in the study area indicate extensive erosion, but limited, localized impacts on streams and limited fine sediment in the main stream draining the area (Marion et al., 2019, 2014; Phillips & Marion, 2019). Given the apparent disconnect between trail erosion and stream sediment, we initiated this study to

CONTACT Jonathan D. Phillips jdp@uky.edu

determine the fate of eroded fine sediments, in the context of sediment dynamics of hillslopes and drainage basins.

Several studies in the 1960s and 1970s (reviewed by Meade, 1982; Walling, 1983) showed that the concept of a direct linkage between an eroding field or hillslope and streams is not applicable in many cases. Time lags, and colluvial and alluvial sediment storage, create non-steady-state relationships between erosion and stream sediment loads, and sediment delivery ratios (erosion divided by fluvial sediment yield) substantially lower than 1.0. By the early 1980s reviews and syntheses of work on fluvial sediment budgets, sediment delivery ratios, and storage and fates of sediment erosion from uplands made it clear that direct "conveyor belt" connectivity and erosion/yield steady states are rare and transient, particularly in drainage basins experiencing accelerated anthropic erosion (Meade, 1982; Walling, 1983). Subsequent work, continuing to the present, has refined knowledge of sediment storage and routing, and linked these ideas to broader concepts of hydrological and geomorphological connectivity (Bracken et al., 2015; Fryirs, 2013; James, 2018; Lisenby & Fryirs, 2017; Thompson et al., 2016). The most poorly understood aspects at present are slope-to-stream delivery, and sediment storage as colluvium and in low-order valleys (Baartman et al., 2013; Fu et al., 2010; James, 2018; Lecce et al., 2006; Merten et al., 2016; Royall & Kennedy, 2016; Slattery et al., 2002). This includes production and delivery of sediment from unpaved roads (Fu et al., 2010) and sediment linkages within low-order, headwater drainage basins (Johnson et al., 2010; MacDonald & Coe, 2007).

We can identify two endpoint situations with respect to sediment connectivity between an eroding unpaved road or trail and a stream system (assuming the two are in the same watershed and potentially hydrologically connected). One is complete disconnectivity, where the stream is completely buffered from the source area, and none of the eroded materialreaches it. At the other end of the continuum, all eroded sediment is delivered directly to the stream. Because erosion and transport are discontinuous and episodic, connectivity in part depends on the time scale involved. In this case, we are concerned with an annual time scale–that is, upland erosion source areas and streams are considered connected if eroded material reaches the stream, on average, within a year. We also acknowledge that connectivity may vary considerably from one erosion and runoff event to the next, and also according to the timing and sequence of events.

Previous research in the Wolf Pen Gap study area has established accelerated erosion and sediment production from a network of off-road vehicle trails (Marion et al., 2019), assessed sediment connectivity of individual erosion features to trails (Phillips & Marion, 2020), and examined impacts on streams (Marion et al., 2014; Phillips & Marion, 2019). A key question emerging from this work is the fate (transport, storage, and sinks) of fine sediment. The goal of this project is to document the fate of fine sediment eroded from the trail system between the eroding source areas and streams. This involves measuring sediment storage on hillslopes and in low-order valleys. The work is motivated by both general questions related to fluvial sediment budgets, and specific questions regarding the fate of eroded sediments in the study area.

It is beyond the scope of this paper to review the literature on erosion and slope to stream sediment delivery on forest roads and trails, but recent reviews and syntheses are given by Anderson and Lockaby (2011), Cambi et al. (2015), Marion and Wimpey (2017), and Benda et al. (2019).

The Wolf Pen Gap (WPG) Trail Complex in Ouachita National Forest, western Arkansas, is a network of unpaved forest roads and trails designated for off-highway vehicle (OHV) use. The trail system has experienced extensive erosion and continues to produce sediment. Despite this, there is limited evidence of fine sediment storage or accumulations in main-valley streams within the Complex (Marion et al., 2014; Phillips & Marion, 2020). Localized erosion features such as rills, gullies, and washed-out wing ditches associated with the trail system are typically strongly connected to channels, as indicated by tracing of flow indicators and sediment from the erosion source to nearby low-order channels (Phillips & Marion, 2020).

Previous work

Marion et al. (2019) found that the WPG trails are all worn down to or near underlying bedrock, with a mean soil truncation of about 40 cm since construction. The trail erosion rate was conservatively estimated 75 to 210 t ha^{-1} yr^{-1} (t = metric tons), depending on sediment availability. These rates are five orders of magnitude greater than those of undisturbed forest (Marion et al., 2019). Underscoring the role of the trails as eroding sediment sources is the fact that limited evidence of erosion was observed in the mostly forested area otherwise, and that sediment production from trails depends strongly on trail width and construction method. Nearly 18 visible erosion features occur per km of trail, with nearly 70% of them rated as having high to very-high connectivity to nearby drainage ways (Phillips & Marion, 2020).

Before 2012, WPG trails commonly had ford-type crossings of stream channels. The geomorphic impacts of 15 such crossings were examined by Marion et al. (2014). Channel effects included increased mud coatings on gravel and cobble particles in the streams downstream of the crossings (10 sites), and in-channel sediment accumulations at six sites. However, observable effects extended only about 200 m or less downstream from the trail crossings.

Fourteen geomorphically active reaches of the channel of Board Camp Creek (the main stream draining the WPG complex) examined by Phillips and Marion (2019) showed significant alluvial accumulations in the form of point, lateral, or mid-channel bars. Ten of the reaches exhibited net sediment storage, but alluvium was dominated by medium to large gravel and cobble material. Finer (<8 mm diameter) sediment eroded from the trail system is apparently not accumulating in the creek, suggesting that it is either transported efficiently through the channel system, and/or that significant quantities of fine sediment are sequestered before reaching Board Camp Creek (Phillips & Marion, 2019). The latter finding was a major motivation for the current study. Among other issues, fine sediments are considered to have the greatest potential adverse impacts on stream ecology (Wood & Armitage, 1997).

Study area

The WPG Trail Complex is in the Ouachita Mountains of western Arkansas and is part of the upper Board Camp Creek drainage basin (Figure 1). The trail complex includes about 70 km of loop trails, with additional FS unpaved roads used by OHVs connecting WPG to county and state roads. WPG trails are variously open to all-terrain vehicles (ATVs), trail

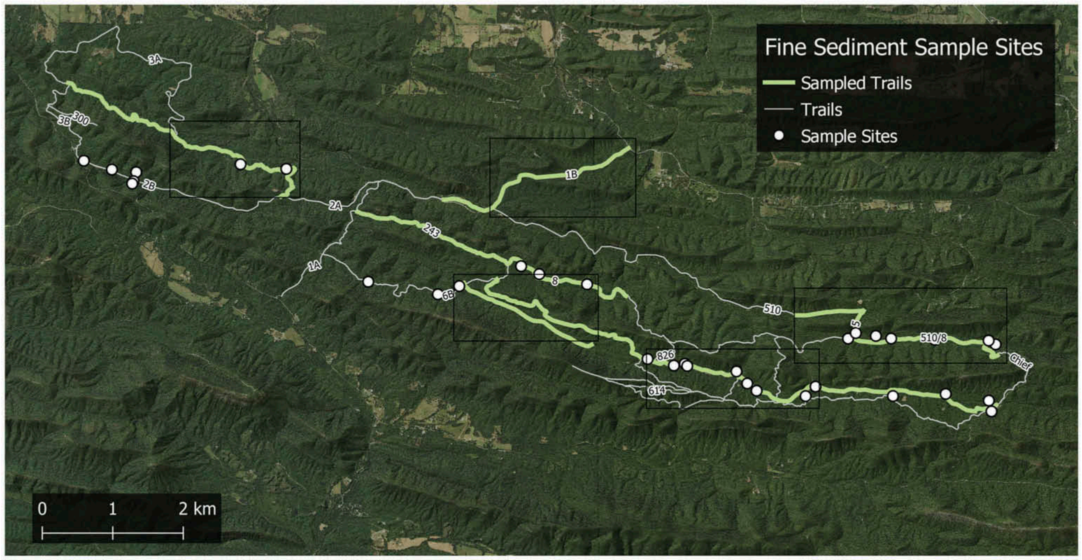

Figure 1. Study area map showing trail sections surveyed for fine sediment accumulations and stream sample sites.

motorcycles, and four-wheel-drive or high ground clearance trucks and utility vehicles, referred to by the umbrella term off-highway vehicles. By far the most widely used are ATVs (also called quads or four-wheelers and including UTVs or utility vehicles), and the trails are referred to in Forest Service signage and literature as *ATV* trails.

Trails were comprised of existing unpaved Forest Service roads and former logging roads when the trail complex was first opened in the early 1990s. Since then, trails specifically intended for ATV use have been constructed, and other trails have been modified to make them more appropriate for ATV use and to minimize erosion and sediment loss. All trails have unpaved, native surfaces (i.e. any construction or maintenance has used on-site materials).

The WPG Trail Complex occurs within the Ouachita Mountains of western Arkansas, a landscape comprised of parallel ridges trending approximately east-west. Peak elevations in the study area are generally 420 to 480 masl. The Ouachitas are geologically complex, composed of extensively tectonically deformed Paleozoic sedimentary rocks consisting of interbedded sandstones, shales, cherts, and novaculites. Steeply dipping and folded strata are common, as are numerous faults and related structures. Weathered bedrock is often exposed in eroded areas such as ridgelines and along unpaved roads and trails.

Soils are predominantly Typic Hapludults (US. Soil Taxonomy) on ridgetops and side slopes, though some Dystrudepts are found in thin-soil areas. 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. Virtually all soils have significant rock fragment content, with volumes of >30% rock fragments the norm, and volumes up to 70% or more possible. Soil textures range from sandy loam to clay, with the former occurring where weathered sandstone is the parent material, with clay to sandy clay loam textures ubiquitous due to the shale content of nearly all parent materials (i.e. shale is interbedded with all other underlying lithologies; Olson, 2003).

The climate is humid subtropical, with hot summers, relatively mild winters, and year-round precipitation. Mean annual precipitation in the WPG area is about 1350 mm, nearly all as rain. The WPG area is >99% forested. Trails, parking areas, and a few scattered clearings are the only unvegetated areas.

Potential fine sediment storage sites

On steep hillslopes, unpaved roads and trails may represent topographic terraces. If significant sediment is produced upslope, the trails themselves may be sites of net deposition. This can be ruled out at WPG, except perhaps in isolated local situations, due to lack of evidence of significant soil erosion other than from trail surfaces, and the fact that essentially all trail surfaces are eroding or recently eroded (Marion et al., 2019).

Colluvial sediment can be stored on the downslope side of eroding trails in the form of rill fans, colluvial or cumulic soils, and depositional berms. This is not a major storage component in WPG, at least over timescales of interest. Little evidence of berms, cumulic soils, or colluvial deposits is evident in the field, though local disturbance by trail construction and maintenance may obscure some evidence. Some rill fans exist, but these nearly all have high or very high connectivity to fluvial channels, and any storage is therefore transient (Phillips & Marion, 2020).

Artificially constructed features do trap a significant amount of sediment at WPG. A program of trail improvements to reduce off-trail sediment export and potential impacts on streams was initiated in 2011 (Poff, 2012; Stinchfield et al., 2011). These improvements include redesigning sections of the trail system and installing more than 700 sediment traps. The traps vary in effectiveness, but in general measurements of volume accumulated over known time periods show that the traps collect substantial amounts of sediment, but would require maintenance every few years to continue to function effectively (Marion et al., 2019). Wing ditches (turnouts associated with water bars) are intended as water control structures to improve road/trail drainage. These typically accumulate eroded fine material, though in some cases they may transition from storage to erosion sites as ditches overflow with sediment or previous deposits are eroded. Some of the trails, especially those that are part of the National Forest road system, have parallel ditches that may accumulate sediments. These are insloped roads and collect runoff that is usually conveyed under the road via culvert. However, these are strongly connected to drainageways and may be considered transient storage (Phillips & Marion, 2020).

Sediment may also accumulate in unchannelled valleys (hollows or zero-order valleys), and in low-order stream channels. Based on the paucity of fine material in Board Camp Creek and the localized nature of impacts at trail crossings of streams (Marion et al., 2014; Phillips & Marion, 2019) we did not expect much alluvial storage in channels. However, we sampled such sites to confirm (or refute) this expectation.

Methods

Trailside deposits

We assessed fine sediment accumulations (FSA) by measuring all detectable accumulation sites along a sampling of trails. 26.3 km of trail was traversed on foot and by OHV to represent the variety of topographic settings and trail types, ages, and usages in the WPG area. Pilot studies confirmed that FSA can be visually identified in the field. This is based on sediments that are unconsolidated and show no evidence of significant pedogenic development, such as soil structural aggregates, horizonation, clay or other illuvial accumulations, or redoximorphic features. Vegetation establishment is quite rapid in the humid subtropical climate of the study area, as is the onset of pedogenesis, so the absence of pedogenic development or vegetation cover is strong evidence of recent deposition. Some fine sediment deposits may occur in very thin (<2 mm) thick layers underneath leaf litter. We did not include these in our assessment.

Our original concern was with clay, silt, and sand fractions (<2 mm diameter). However, these are so commonly and thoroughly intermixed with small gravel (in this case 2–8 mm diameter), that to facilitate extensive sampling we used a working definition of fine sediment as clay, silt, and sand, and 2–8 mm diameter gravel, if mixed with <2 mm material. In the Wentworth particle size classification system, clay particles have a diameter of <0.002 mm, silt is 0.002 to 0.0625 mm, and sand 0.0625 to 2 mm. The finest gravel (granule) category is 2–4 mm, and 8 mm is the upper limit of the fine pebble category.

Sampling of sites other than fluvial channels was restricted to sites where the sediment can be attributed to erosion from the trail. In the sampled areas we examined all unvegetated or minimally vegetated surfaces in the following settings:

- Low-order stream channels (referred to hereafter as small streams) adjacent to or crossed by trails. Crossings of these smaller streams are either ford-type crossings that are dry except in wet weather, or small pipe or culvert crossings.
- Unchannelled headwater valleys and hollows.
- Local topographic depressions.
- Surficial deposits associated with water and sediment control structures (e.g. wing ditches, sediment traps).

Thickness of fine sediment was measured by manually probing or excavating the unconsolidated material to underlying soil or bedrock. Depending on the specific site characteristics this was accomplished with soil probes, steel rods (rebar) hammered to bedrock or cohesive soil, or shallow trowel excavation. In small-stream channels, the channel boundaries are bedrock or cohesive materials that provide a clear demarcation between FSA and other materials. Cohesive soil or bedrock also constitutes the underlying surface in some of the other depositional settings, but sometimes buried soil A-horizons or organic layers are underneath the deposits. Depth of the FSA was measured using a folding ruler, to the nearest cm. If a thin cover of FSA was evident but too thin to reliably measure, this was recorded as "veneer."

The surface area of the FSA was surveyed using a laser level and prism, survey tape, or folding ruler, depending on the size of the feature. Accumulation area was calculated using length times mean width, with the number of width measurements increasing with the length and complexity of the accumulation. Mean depth of FSA was based on at least five measurements, with at least one depth measurement per square meter of surface area for larger deposits.

The location of each FSA feature at its closest point to the trail was recorded using GPS. The longitudinal slope along the thalweg of selected ephemeral and small-stream FSAs was surveyed using the laser level and prism.

These methods are conservative and results should be taken as *minimum* estimates. They do not include deposits that might not be visually evident, or older colluvium obscured by vegetation or soil development.

Stream channel deposits

A stratified random selection of potential sample locations was based on landform associations and channel types. Three landform associations occur within the study area. Valley side slopes and ridges (VSR) encompass the ridgelines and side slopes of primary and secondary valleys. Ridgelines are narrow, slope lengths are long, with typical ridgetop-to-valley bottom distances of 400 to 500 m, though the slope gradients and curvatures are typically quite variable. Relief is relatively high; typically 120–215 m. The benchlands and ridge saddles (BRS) unit occurs at middle elevations, predominantly on north-facing slopes. Terrain consists of gently to moderately sloping, broken or knobby terrain. Predominant local peak to saddle slope lengths are short to moderate (<50 to 300 m). External relief is moderate and internal relief is low to moderate. Valley bottoms (VB) occur at the lowest elevations within primary valleys. Terrain consists of active channel areas, flood plains or terraces (if present), or lower footslopes. Slope lengths are dominated by local microtopographic features and are thus short to very short (<50 m) and relief is low.

The channel network to be classified was derived from one developed by Guarneri (2013). Guarneri (2013) found that using an inverse distance weighted interpolation of 10-m digital elevation model data to produce a 5-m model, and a constant mean flow accumulation of 4 ha produced the most accurate predictions of channel initiation locations. The digital network derived from these points was then edited using ArcGIS to correct minor errors (mostly segment gaps) and remove first-order segments < 10 m long which we deemed were too short to be confident of their existence. The derivation process did not capture some low-order channels that occur within the BRS and VB associations. Low internal relief within these associations prevents these channels from always being detected in the digital modelling, while heavy canopy cover and narrow widths hide them during aerial imagery inspection. These excluded channels were sampled as part of the trailside FSA sampling.

Channels were classified into seven categories. Three (Lower Valley 1, LV2, LV3) are confined to VB settings along Board Camp Creek, with estimates of fine sediments based on alluvial soil mapping and main channel field surveys. UV1 and UV2 channels (UV = upper valley) occur within BRS and VB associations. UV1 streams typically do not have depositional features visible on aerial imagery within the channel. Low sinuosity indicates the channel is confined and the channel generally fills the valley bottom. The channel adjacent slopes are generally short but can be moderate to long where channel occurs at the boundary between BRS and VSR. The UV2 type is confined within narrow valley trenches but exhibits meandering within these boundaries. Small depositional features (bars) are visible but very limited in extent. UV1 and UV2 channels generally have drainage areas ≤3 or >3 km^2, respectively.

H1 and H2 channel types are low-order headwater channels. Note that we refer to stream order only in relative terms, as we found that results obtained through "blue line" analysis of maps and GIS stream coverages and by digital elevation model analyses showed results that differed by an average of two orders for any given channel segment. H1 and H2 channels occur in the VSR and BRS landform associations, and have no deposition features visible on aerial imagery. H1 channels are steeper and have longer, steeper valley side slopes than H2.

Once the streams were classified, the total length of H1, H2, UV1, and UV2 channels was determined and a stratified sampling scheme developed to represent their proportional presence in the study area. While some sampled reaches were a short distance up- or downstream of trail crossings, we avoided sampling channel segments immediately adjacent to trails to avoid possible effects of trail maintenance and construction of features such as trail-edge berms and culverted crossings.

In all sampled H1, H2, UV1 and UV2 channels, the longitudinal profile was surveyed using a hand level and stadia rod. Banktop channel widths were measured at the beginning and end of the study reach. Reach lengths were at least 20 times width at the starting point. These data were used with the Shields function to estimate the threshold shear stress to entrain an 8 mm diameter particle.

$$\tau_c = Kg\left(\rho_s - \rho_w\right)D \tag{1}$$

where is the critical or threshold shear stress, g is the gravity constant, ρ_s, ρ_w are the densities of sediment and water, respectively (taken to be 2.65 and 1.00 g cm^{-3}), and D is particle diameter (mm). The value of the constant k is 0.03, the value recommended for steep cobble-bed streams (Jarrett, 1990).

This yields a value of τ_c = 3.88 N m^{-2}. Then, the mean boundary shear stress in Equation (2) was solved for R (hydraulic radius, assumed to be approximately equal to mean depth) to determine the depth required to entrain particles ≤8 mm for the range of S (slope) values measured in the field.

$$\tau = \rho_w g\ RS \tag{2}$$

Widths were also measured at the transition between hydraulic units identified in the field (riffles, pools, runs). In the smaller channels (H1, H2) the area of each unit was determined (length X width), and FSA was measured as described for trailside accumulations above. At least six measurements per unit were taken, including measurements of zero where no fine sediment occurred. These were averaged to determine a mean depth for each unit. This sampling detail was not feasible in the larger (UV1, UV2) channels. There, each width measurement site was treated as a transect sample. For each area of FSA encountered along the transect, depth (or the mean depth of several samples for larger accumulations) was measured, along with its associated length along the width transect. This information was extrapolated using the area of the hydraulic units to determine total fine sediment storage for each unit.

To better describe the grain-size composition of FSAs within small channels, substrate samples from four sites were collected and analyzed. Bulk samples of 150–250 g were excavated from measured FSA deposits by digging vertically about 10 cm with a hand trowel. Each sample was oven-dried and analyzed using a half-phi sieve stack and standard gravimetric procedures.

In each sampled reach the maximum mobile clast size was measured as a potential index of stream competence. Two were selected, one each from the up and downstream half of the reach. These were stones completely within the channel, with no mud coats, moss or biofilms, and not embedded in or interlocked with other material. The median diameters were measured in the field.

Tests for significant differences among stream types were based on unpaired t-tests, with $\alpha = 0.05$.

FSA in larger streams

Fifteen ford-type OHV trail crossings of streams were examined by Marion et al. (2014) to assess geomorphic impacts and to compare reaches up- and downstream of the crossings. Results and field notes from these sites were reexamined with respect to fine sediment storage in the channels. While quantitative measurements of sediment accumulation were not systematically made at all sites, at a minimum, the presence of any fine sediment deposits, and mud coatings on rock fragments and exposed bedrock were noted.

Sediment storage and channel erosion in the highest order, main channel in the study area (Board Camp Creek) was assessed in 14 representative, geomorphically active reaches by Phillips and Marion (2019). Here, in-channel sediment storage is dominated by coarse (gravel to boulder) sediment, but field notes and results were reassessed with respect to evidence of storage (or remobilization by bank erosion) of stored fine sediments.

Floodplain sediment storage

Because our primary concern was fine sediment storage between trail erosion sites and streams, and due to practical constraints, we did not attempt field measurements of recent FSA on stream floodplains. However, to determine whether substantial amounts of fine sediment are sequestered in floodplains, and to get at least a broad general perspective of this component of fine sediment storage in the Board Camp Creek watershed, we estimated floodplain fine sediments in alluvial soils. Because alluvial soils accumulate over longer periods and include material that predates the trail system, these estimates are not directly comparable to our field measurements but are presented for completeness.

Floodplains are not extensive on the smaller streams in WPG and are discontinuous on the larger streams. Soil survey data were used to estimate floodplain sediment storage using the US. Department of Agriculture's Web Soil Survey (WSS; https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). The WSS data for the WPG are based on the Soil Survey of Polk County, Arkansas (Olson, 2003).

Area of alluvial floodplain soils was determined using the map data, and modal thickness and fine sediment proportion using soil attribute data, soil profile descriptions (Olson, 2003), and our own measurements of bank exposures of alluvial soils. Most of this area occurs along Board Camp Creek, but small patches along other streams were also included in the alluvial storage estimates.

There exist scattered locations where recent floodplain deposition is clearly attributable to the trail system (Phillips & Marion, 2019), but much of this material is older.

Mud coats

Some fine sediment exists as muddy coatings on cobbles and boulders and bedrock exposed in the channel. To get a general idea of whether this is significant as a source of fine sediment storage (as opposed to an indicator of sediment transport and deposition dynamics and related flow dynamics) we sampled three sites and analyzed a total of five samples. While not rare throughout the study area, the abundance and thickness of mud coats at the sampled sites (by visual assessment) all appeared considerably muddier than typical.

The mass of mud coats (all in the silt and clay size ranges) was determined by carefully washing all surface sediment into a clean, tared crucible. Excess water was removed by oven drying at 103°C until all water was evaporated. Organic matter was removed by ignition in a muffle furnace (600°C for 6 hours). Sediment was weighed to the nearest 0.01 g using a calibrated scale.

Surface area of each clast was determined by measuring the plan dimensions of a sheet of paper to the nearest 0.1 mm, and then weighing to the nearest 0.01 g. Mass/area was then computed for the measured sheet. The coated surface area of each sample clast was then tightly wrapped in an identical sheet of paper, trimming away all excess paper and ensuring no overlaps in coverage. The trimmed paper was then weighed, and the computed area determined based on (mass of trimmed paper)/(mass/area of measured sheet).

Results

Table 1 shows the estimated fine sediment storage in various settings. Details are given below.

Trailside fine sediment storage

Along the 26.3 km of trail surveyed, we identified 126 trailside FSA sites. This is a mean of 8.4 per km of trail, compared to the mean of about 18 erosion features per km of trail

Table 1. Estimated total fine sediment storage in WPG drainages.

Storage	Basis for extrapolation	Volume (m^3)
FSA features adjacent to trails	Total measured FSA total for 26.3 km of sampled trails extrapolated to 79.5 km total distance	1,882
H1 Streams	Measured FSA per m of channel extrapolated to entire 28,107 m length	1,827
H2 Streams	Measured FSA per m of channel extrapolated to entire 30,211 m length	1,178
UV1 Streams	Measured FSA per m of channel extrapolated to entire 20,675 m length	496
UV2 Streams	Measured FSA per m of channel extrapolated to entire 13,984 m length	559
LV1,2,3 Streams	Phillips & Marion, 2019	Negligible
Alluvium	Mapped alluvial soil area adjusted for estimated fine sediment content (51% mean)	261,324
Mud coats	Limited exploratory sample & analysis	Negligible?
Other	Interstitial fines in coarse sediment deposits (e.g. cobble bars); unmapped floodplain alluvium; colluvial soils	Unknown

reported by Phillips and Marion (2020). Natural topographic and drainage features were the dominant FSA sites examined, including 45 channels that were dry at the time of sampling (36% of the total) and 26 channels with flow (21%). These were trailside channels such as that shown in Figure 2, and are not included in the stream sampling. The accumulation sites also included six hollows or unchannelled valleys, two of which had underlying culverts. Water or sediment control features accounted for 45 FSA sites (35%), including 15 wing ditches and 30 sediment traps (Figure 2).

Small, low-order channels account for more than two thirds of the total measured sediment storage, and hollows for another 15.5% (Table 2). Thus, natural topographic drainage features represent nearly 83% of the total, with constructed drainage and sediment control features accounting for most of the rest. Note that while the wing ditches had been in place for more than 20 years, the sediment traps were recently constructed (≤1 year before sampling; Marion et al., 2019), accounting for the low FSA measurements at those sites. Given their relatively short accumulation period, and our observation that many partially filled traps occur elsewhere in the WPG system, the amount of fine sediment sequestered in these features will likely increase.

With the exception of the recently constructed traps, the mean depth of FSA was remarkably consistent among the features (see Table 2). This may be coincidental, though we speculate that general consistency in the size of obstructions (cobble-size clasts) may play a role.

Figure 2. Trailside fine sediment accumulations. Left, a filled sediment trap. Right, a silted natural ephemeral channel.

Table 2. Fine sediment storage in trailside accumulations.

Feature	N[a]	%FSA[b]	Storage (m[c])	Mean Storage (m[c])	Mean depth (cm)	% largest[c]	% total FSA
Dry channel	45	62.2	303.0	10.82	13.7	48.5	47.1
Flowing channel	26	65.4	128.6	7.56	15.8	29.6	20.0
Hollows (unchannelled valleys)	6	100.0	99.9	16.65	15.8	91.3	15.5
Wing ditches	15	100.0	92.1	14.09	14.1	54.5	14.3
Sediment traps	30	50.0	13.7	0.91	5.4	31.5	2.1
Other	2	100.0	5.4	2.70	12.1		0.8
Total	124	64.7	642.7	5.18	12.3		100.0

Number of features.
Percent of features with measurable fine sediment accumulation.
Percent of total fine sediment storage accounted for by the single largest deposit.

Results also suggest the importance of high-accumulation "hotspots" (Figure 3). The single largest measured sites accounted for about 50% each of ephemeral channel and wing ditch deposits; nearly 30% of the FSA in first-order channels; and more than 90% of FSA in hollows.

The measured FSA amounts to a mean of about 24.5 m^3 per km of trail, based on total measured volume divided by sample length. Extrapolated to the entire 79.5 km trail network, this would result in an estimated 1,944 m^3. Given a measured bulk density of 1.26 t m^{-3}, this amounts to about 123 t per ha of trail surface (total trail length times mean width).

Headwater and Upper Valley channel sediment

We measured total fine sediment deposits of 61.4 m^3 in 33 H1, H2, UV1, and UV2 channel samples. This amounts to means of 46.0 m^3 per kilometer of channel length, and

Figure 3. Fine sediment accumulated behind a log in an unchannelled valley (hollow).

0.030 m^3 per m^2 of channel bed area, equating to a mean depth of <3 cm. FSA examples for these channel types are shown in Figure 4.

Table 3 compares sample sites potentially subject to runoff and sediment input from trails to those with no trail effects. As expected, more fine sediment is found in trail-influenced reaches. However, the differences are not statistically significant according to t-tests. This includes a test using only H1, H2 channel types, as all but one UV site had trail effects. FSA per unit bed area suggests an accumulation of 2 to 3 cm if spread evenly. However, measurements show that FSA is highly concentrated both within and between patches or sub-reaches.

Comparisons among low-order stream types (Table 4) might suggest some differences between channel types, but none of the differences among the four types (separately or aggregated) is statistically significant.

Sediment mobility

The maximum mobile clasts ranged from 22 to 320 mm in diameter, with an overall mean of 173 mm. Table 5 shows comparisons between trail-impacted and non-impacted sites, and among stream types. No statistically significant differences exist between those

Figure 4. FSA examples in sampled headwater streams. On left, a typical reach with very little FSA. On right, a localized accumulation behind coarse woody debris.

Table 3. Fine sediment storage in low-order channels (mean values; standard deviations in parentheses).

	No trail effects (n = 12)	Trail effects (n = 21)
FSA volume (m^3)	1.21 (0.99)	2.23 (2.41)
Vol./km channel length	32.0 (25.0)	55.0 (68.0)
Vol./m^2 channel bed	0.021 (0.014)	0.036 (0.048)

Table 4. Fine sediment storage by stream type (mean values; standard deviations in parentheses).

	H1 (n = 12)	H2 (n = 12)	UV1 (n = 5)	UV2 (n = 4)
FSA volume (m^3)	2.28 (2.73)	1.53 (1.20)	1.25 (1.03)	2.37 (2.39)
Vol./m channel length	0.065 (0.082)	0.039 (0.029)	0.024 (0.024)	0.040 (0.037)
Vol./m^2 channel bed	0.051 (0.056)	0.024 (0.015)	0.010 (0.013)	0.011 (0.008)
	H1 & H2		UV1 & UV2	
FSA volume (m^3)	1.90 (2.19)		1.75 (1.78)	
Vol./m channel length	0.052 (0.064)		0.032 (0.031)	
Vol./m^2 channel bed	0.037 (0.036)		0.011 (0.012)	

sites potentially impacted by trails and those not. The values are higher in UV1 and UV2 as compared to H1 and H2 channels, with the difference statistically significant.

Table 6 shows slope gradients for small channels where trailside FSA was measured, and for sampled stream segments. The mean boundary shear stress equation was used as described in the methods section to determine the flow depth required to entrain particles ≤8 mm for the range of S (slope) values shown in Table 6. Results are shown in Figure 5.

Grain size

All four of the stream FSA samples analyzed for grain size showed very small amounts of silt and clay, ranging from 0.28 to 11.8% (Figure 6). In most cases, it was difficult to collect samples without a significant amount of fine gravel; which was 60% or more in three samples. Sand content ranged from about 7 to 85%.

Crossing sites

At the 15 crossing sites (all H2 or UV2 channels) studied by Marion et al. (2014) field observations included the extent to which exposed bedrock and coarse clasts exhibited mud coatings (categories of none, few, common, and extensive), and any fine sediment

Table 5. Maximum mobile clasts (diameter, mm).

	N of samples	Range	Mean	St. Dev.
All	66	22–320	173	69
All upstream	33	62–320	172	72
All downstream	33	22–290	173	68
No trail impacts	24	22–320	167	78
Possible trail impacts	42	62–290	175	66
H1	12	22–270	148	66
H2	12	62–285	151	65
UV1 + UV2	9	140–320	223	55

Table 6. Field-measured channel slopes.

Channel type	Minimum	Maximum	Mean	Standard deviation
Dry trailside	0.0413	0.1531	0.0983	0.0397
Flowing trailside	0.0397	0.1341	0.0772	0.0334
H1 & H2	0.0229	0.1062	0.0568	0.0231
UV1 & UV2	0.0165	0.0478	0.0269	0.0097

Table 7. Alluvial soils mapped in the study area (USDA Web Soil Survey). The range of percent fines is taken from the map unit descriptions in Olson (2003) and the official series descriptions.

Map unit	Area (ha)	% Fines[a]
Ceda very cobbly fine sandy loam, 0% to 3% slopes frequently flooded	211.0	30 to 65 (35)
Kenn gravelly fine sandy load, 0% to 3% slopes occasionally flooded	5.1	35 to 70 (68)
Kenn-Ceda complex, 0% to 3% slopes, frequently flooded	150.5	30 to 65

Number in parentheses is percent fines (silt + clay sizes) calculated from profile description in the soil survey of Polk County, AR.

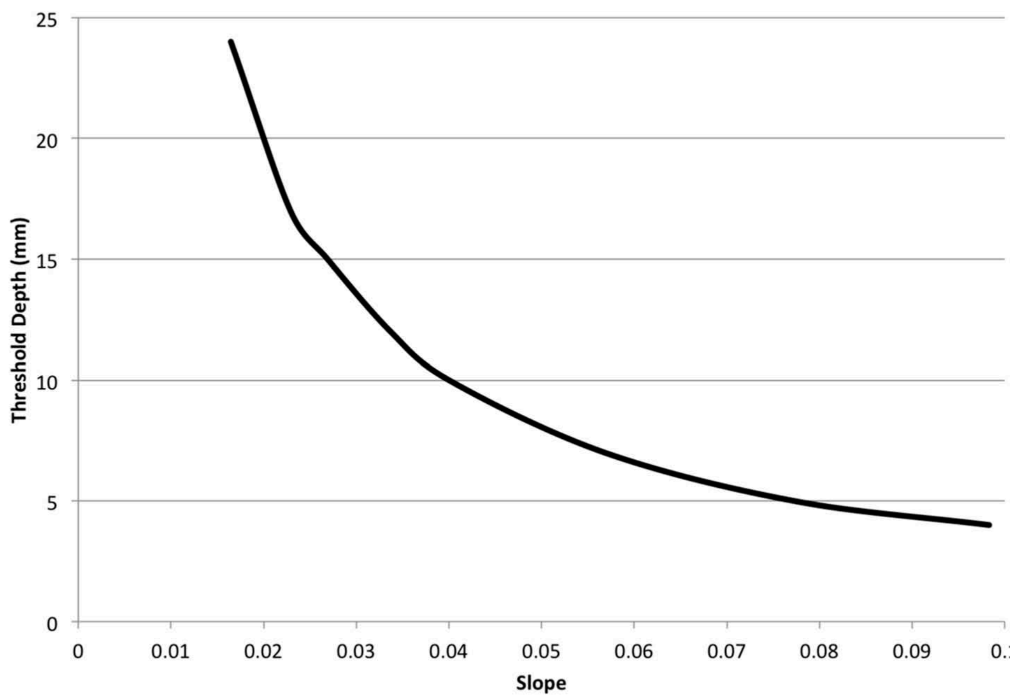

Figure 5. Minimum depth necessary to transport an 8 mm median diameter particle for the range of slopes shown in Table 6.

accumulations. Mud coats were present downstream of the trail crossing at all 15 sites; at all but one site some mud coatings were also found upstream. However, as shown in Table 5 of Marion et al. (2014), in some cases these were present only in pools or backwater areas upstream, and in many cases were more prevalent downstream of the crossings.

For the most part, other fine sediment deposits were absent, rare, or isolated. Three sites, however, had braided subreaches or sediment plugs. As Marion et al. (2014) noted, visible or measurable evidence of geomorphic impacts was generally confined to the vicinity of the crossing; at 200 m or greater, downstream impacts apparently attributable to the trail crossing were not visible.

Mud coats

The five sampled clasts were all in the coarse pebble category (45–64 mm median diameters). Surface areas ranged from 75.4 to 133.3 cm^2. Mass of mud coats per unit

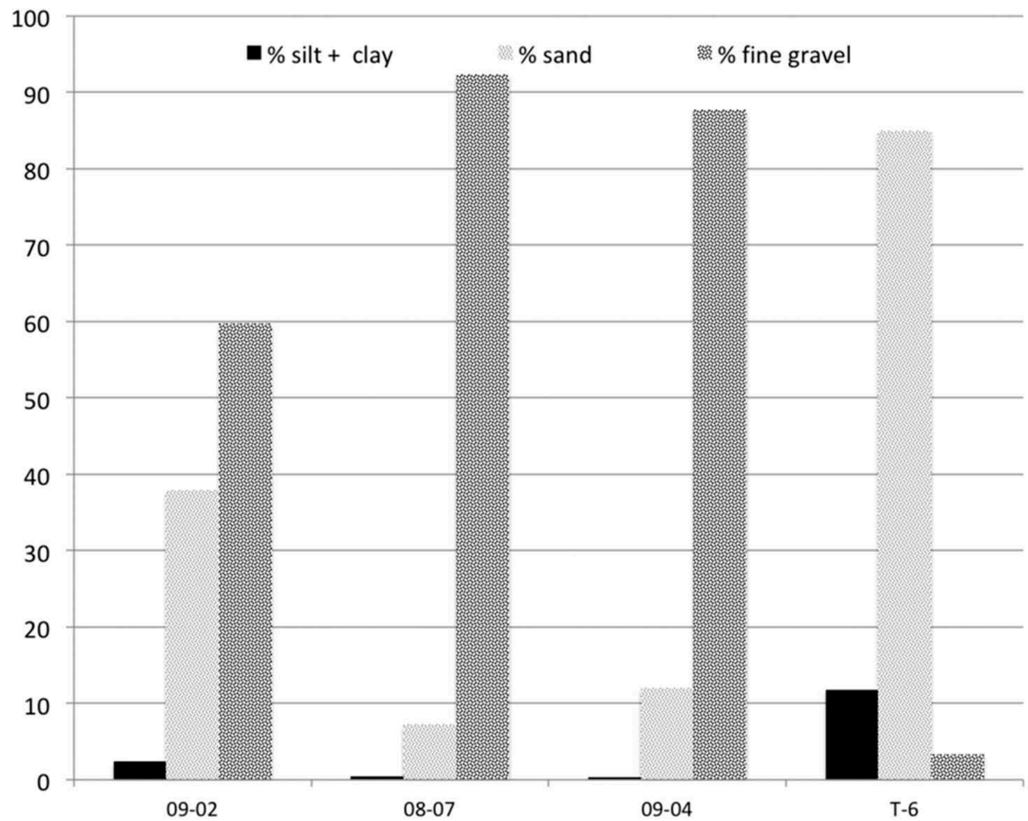

Figure 6. Grain size of low-order stream sediment samples. Fine gravel, in this case, includes particle diameters 2–8 mm.

area ranged from 22.8 to 62.0 g m^{-2}, with a mean of 42.4. This is three orders of magnitude less than sediment stored in other forms in stream channels (assuming a conservative density of about 1000 kg m^{-3}). This suggests that mud coats, while indicative of elevated silt/clay input and possible aquatic habitat degradation, are not a significant source of sediment storage–at least, based on this very limited exploratory analysis.

Lower Valley channel sediment

Few fine sediments are stored within the channels of LV1, LV2, and LV3 sections of Board Camp Creek. Mid-channel, point, and lateral bars are primarily cobble bars, with relatively little sub-gravel size material (Phillips & Marion, 2019). However, some fine sediments are deposited during overbank flood flows and stored as floodplain alluvium. Scattered fresh sediment deposits and flow indicators on floodplains such as wrack lines and bent vegetation indicate that overbank flow does occasionally occur. Even floodplain deposits are typically rich in coarse fragments, however.

Testing of soils occurring within the study area (Olson, 2003) indicates that sand-size and smaller sediment ranges between 35 and 68% by volume of mapped alluvial soil types. Three alluvial soil map units are mapped within the WPG area (Table 6), the vast majority along Board Camp and Gap Creeks, accounting for a total of about 367 ha. The Ceda series typically has 35% to 70% coarse fragments by volume, with 30% to 65% fines (clay to sand). Kenn series soils are about 35% to 70% fines. The Kenn-Ceda complex mapped in the area is about 60% Kenn and 30% Ceda soils (and 10% others). The Kenn series (Ultic Hapludalfs) has pedogenic evidence of significant residence time, including an argillic horizon, clay films indicating translocation, and weak subangular blocky structure in the subsoil. The Ceda (Typic Udifluvents), by contrast, is minimally developed, with an A-C profile and no structural development below the A horizon (Figure 7).

Bank erosion features were measured in 14 sample reaches of Board Camp Creek by Phillips and Marion (2019), where a full description of the sampling scheme and field methods can be found. Two of these sites were on UV2, two on LV1, six on LV2, and four on LV3 reaches. Three of the study reaches had no bank erosion features, and some features were eroded into upland (non-alluvial) material, or were in the form of chute channels. Alluvium was exposed by 23 of the features, shown in Table 8. Material of the exposed alluvium was recorded in field notes, but not previously published. Descriptions

Figure 7. Example exposures of Ceda (top) and Kenn (bottom) series.

of coarse, gravelly & cobbly, cobbly, stony, and gravelly were recorded where the exposure had 15% to 50% rock fragments by volume. The very coarse description was used where rock fragment volume was >50%. The absence of one of these descriptors implies <15% rock fragments. Note that these descriptive categories differ from the US. Department of Agriculture classification, whereby 15–35% rock fragment content is considered gravelly, 35–60% is very gravelly, and 60–90% extremely gravelly.

The mean bank height (relative to the adjacent channel bed) is a reasonable conservative estimate of the thickness of potentially remobilizable alluvial material. This indicates a range of about 0.5 to 4.7 m (mean 1.44 m, standard deviation 1.03 m; Table 8). A total area (within WPG) of 366.6 ha and a mean thickness of 1.44 m gives a total volume of 512,400 m^3, with a typical bulk density of 1.5 t m^{-3} (Olson, 2003). Assuming sand, silt, and clay content of 30% to 65% by volume, this represents a rough estimate of 154,000 to 333,000 m^3 of fine sediment storage in floodplain alluvium. This represents about 51 to 111 m^3 per ha of drainage area.

Discussion

Fine sediment storage

Measured fine sediment storage in trailside accumulations amounts to about 643 $m^{3.}$ With a mean bulk density of 1.26 tonnes m^{-3}, and extrapolated to the entire trail network, this amounts to 123 tonnes per hectare of trail surface (compared to 75–210 t ha^{-1} yr^{-1} for soil loss from the trails estimated by Marion et al., 2019). As trailside FSA represents only a portion of eroded trail sediment, this suggests a residence time for FSA of <1 year. We

Table 8. Alluvium exposed in bank erosion sites along Board Camp Creek. Reach numbers refer to sample reaches of Phillips and Marion (2019), and are in upstream to downstream order.

Reach	Material	Mean Bank Height (m)
1	Very coarse alluvium	1.00
1	Stratified alluvium including very coarse, fine, & coarse layers	1.16
1	Coarse alluvium	0.81
2	Very coarse alluvium	1.38
2	Very coarse alluvium	0.90
3	Cobbly alluvium overlain by finer, silty alluvium	1.30
3	Silty alluvium overlying stony soil	1.10
3	Gravelly alluvium overlying very coarse alluvium	1.44
4	Gravelly & cobbly alluvium	1.46
5	Gravelly & cobbly alluvium	4.24
5	Gravelly & cobbly alluvium	4.68
6	Gravelly & cobbly alluvium with rock-free finer pockets	1.30
8	Gravelly & cobbly alluvium	
8	Gravelly & cobbly alluvium	1.28
9	Gravelly & cobbly alluvium	0.80
9	Gravelly & cobbly alluvium	1.47
10	Gravelly & cobbly alluvium	1.00
10	Gravelly alluvium	0.95
11	Fine alluvium with gravel & cobbles	1.46
12	Fine alluvium overlying gravelly & cobbly alluvium with finer pockets	1.00
12	Fine alluvium overlying gravelly & cobbly alluvium with finer pockets	1.37
12	Fine alluvium overlying gravelly & cobbly alluvium with finer pockets	0.60
12	Fine alluvium overlying gravelly & cobbly alluvium with finer pockets	0.90

Note that this represents net storage over longer time periods and includes alluvium deposited before the trail system was established, and from sources other than trail erosion.

only measured unvegetated FSA with no pedogenic development, and none of the excavated sites contained buried plant litter. These field indicators are also indicative of short residence times of <1 year, as vegetation establishment is quite rapid in the humid subtropical climate and litterfall is significant in the forest setting. These observations, coupled with the high sediment connectivity of erosion features documented by Phillips and Marion (2020) suggest that many of the FSAs are transitory, pass-through accumulations.

The potential mobility of the FSA material is illustrated by the steep channel slopes of the channel trailside FSAs, and of the sampled headwater and upper valley streams. The slopes are such that mean flow depths of <25 mm (< 1 inch) are sufficient to transport small gravel particles, along with sand and silt. The transportability of gravel is supported by the presence of mobile clasts in the sampled channels averaging about 150 mm in headwater and 220 mm in upper valley channels.

Results with respect to trailside FSA may be contingent on when sampling occurred. Sampling for the sediment connectivity study was conducted in May 2012. This included 14.9 km of trail that were also surveyed for FSA. Phillips and Marion (2020) recorded 156 "overflowing wing ditches" and 36 "silted natural ephemeral channels" – features that would have been included in a trailside FSA survey. The former are wing ditches that appeared to have filled with sediment, and had visually evident sediment being exported from the feature. The latter were recorded where the channel upslope of the trail crossing had no evident channel erosion or sediment accumulation, but downstream of the trail were obvious recent deposits of trail-derived sediment. Even discounting the fact that an additional 10 km of trail was sampled in 2012 as opposed to the FSA sampling in March 2014, and the different purposes and goals of the two studies, it appears that visually identifiable accumulations may have been less common in 2014. The Mena, AR weather station recorded 48 mm of precipitation 2 days before sampling began on 18 March, making for wetter conditions than during the 2012 sampling, so recent runoff is unlikely to account for the difference. Use levels of the trails is a more likely explanation, as spring, in general, is a higher use period than winter (though no quantitative data for either period are available).

Results point to the importance of natural topographic features as FSA sites. Channels and hollows account for about 83% of the total, while wing ditches and sediment traps had about 16% (though, as noted, sediment trap sequestration is likely to have increased). The fact that more than two thirds of the total occur in channels is consistent with the high sediment connectivity of erosion features and the fluvial system found by Phillips and Marion (2020).

For all categories of fine sediment accumulations, the single largest deposit accounted for about 30% or more of the total – 91% for hollows. These hotspots are found where a topographically suitable storage site occurs downslope of an area of above-average rates of, or recent, trail erosion. Because in many cases trail erosion occurs without evident gullies or rills (underlying bedrock is exposed at or near the surface throughout the trail network; Marion et al., 2019), this suggests that these accumulation hotspots are effective ways to identify erosion hotspots.

Relatively small amounts of fine sediment are stored in low-order stream channels, with no conclusive evidence of greater volumes per unit of channel bed area in sites potentially affected by ATV trails compared to those with no trail effects. The low storage amounts (4,060 m^3 estimated for all low-order streams) and lack of silt and clay indicate that fine sediments are generally highly mobile once reaching streams.

Mud coats on coarse clasts do not appear to be a large contributor to sediment storage, though additional data are needed to corroborate this. These coats are, however, an indicator of sites of potential adverse water and habitat quality impacts.

The total fine sediment storage in trailside accumulations and low-order streams, extrapolated to the entire study area, amounts to 5,942 m^3 (Table 1). The total estimated fine sediment in alluvial soils is nearly 44 times as much (about 261,000 m^3), but cannot be directly compared to the other measurements due to the longer time frame for accumulation and generally unknown source. Nearly all the trailside FSA occurs in drainageways or in constructed features and can thus be considered highly mobile. The small-stream accumulations are also highly mobile, as are deposits in the main channel (Phillips & Marion, 2019). The alluvial storage, by contrast, is mobilized only by bank erosion and occasional surface stripping during high flow events.

Fluvial sediment systems

Results of this study show significant amounts of fine sediment storage, amounting to a substantial portion of trail erosion. This supports the notion of non-steady-state relationships (at the annual to decadal time scale most relevant to land use and management) between erosion and sediment yield, and significant storage and time lags in the drainage basin sediment system. On the other hand, there is little evidence of long-term sediment storage or fine sediment sinks. Thus, while WPG does not fit a conveyor belt metaphor, a somewhat intermittent, leaky conveyor belt would perhaps be appropriate.

With reference to the endpoint situations – direct delivery of eroded sediment to streams vs. complete disconnectivity – WPG is closer to the former than the latter, at least at the annual time scale. This likely reflects the linear nature of the eroding areas, and their frequent proximity to streams. GIS analysis shows 480 locations were trails intersect stream channels, and an additional 2.15 km of trail length where the trails are within 15 m of channels. The intersections include channels of all sizes, and crossings including bridges, culverts and arches, fords crossing perennial channels, and wet-weather fords that may often be dry. The number of actual crossings is uncertain due to the spatial resolution of the trail layer of the GIS, in areas where trails follow valley bottoms or along the upper edge of steep valley wells. However, any apparent crossings that were incorrectly counted occur where trails are within a few meters of channels and do reflect sites of very high trail-channel connectivity.

Conclusions

Fine sediment storage in trailside accumulations, extrapolated to the entire trail network, amounts to 123 tonnes per hectare of trail surface (compared to 75–210 t ha^{-1} yr^{-1} for soil loss from the trails). Because these FSAs are unvegetated, contain no litter deposits or pedogenic development, and represent only a portion of eroded trail sediment, this indicates a residence time of <1 year. Many of the FSAs are transitory, pass-through accumulations.

Natural topographic features – channels and hollows – are the most important deposition sites, accounting for about 83% of the total (though, as noted, sediment trap sequestration is likely to have increased). More than two thirds of the total occur in channels, indicating high sediment connectivity of erosion features and the fluvial system. Hotspots are also important, with the single largest deposit accounting for 30% to 90% of the total for all types of FSA. These accumulation foci are effective ways to identify erosion hotspots, as obvious erosion features such as rills or gullies are often absent.

Only small amounts of fine sediment are stored in stream channels, with limited evidence of greater sequestration in sites potentially affected by ATV trails versus those with no trail effects. The low storage amounts (4,060 m^3 estimated for all low-order streams) and lack of silt and clay indicate that fine sediments are generally highly mobile once reaching streams. Overall, the fine sediments appear to be highly mobile and not subject to long-term storage.

While the results of this study support the idea of non-steady-state relationships between erosion and sediment yield, there is little evidence of long-term sediment storage or fine sediment sinks occurring.

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ORCID

Jonathan D. Phillips http://orcid.org/0000-0003-0283-6023

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