The Effects of Off-Highway Vehicle Trails and Use on Stream Water Quality in the North Fork of the Broad River

Article · January 2019

DOI: 10.13031/trans.13098

Chelcy Ford Miniat
USDA Forest Service, Southern Research Station, Center for Forest Watershed Research, Coweeta Hydrologic Lab

THE EFFECTS OF OFF-HIGHWAY VEHICLE TRAILS AND USE ON STREAM WATER QUALITY IN THE NORTH FORK OF THE BROAD RIVER

C. F. Miniat, P. P. Clinton, L. K. Everage

ABSTRACT. *Managing forests for recreational benefits, such as off-highway vehicle (OHV) use, as well as other ecosystem services, such as clean and abundant water, can often present challenges for land managers when one ecosystem service conflicts with another. We conducted research in the Chattahoochee-Oconee National Forest to determine if the presence and use of OHV trails were associated with greater total suspended solids (TSS) concentrations and turbidity in streams during storm events in 2015-2016. We used a paired-watershed approach, with a treatment watershed containing the Locust Stake OHV trail system on the North Fork of the Broad River, and a reference watershed (Kimbell Creek) similar in all respects except for the presence and use of OHV trails. During the study period, mean streamflow rates across all sampling times were 19% greater, but mean stormflow rates were 29% less, at Locust Stake compared to Kimbell Creek. During storm sampling, the average storm TSS concentration was greater at Locust Stake (101.1 mg L^{-1}) than at Kimbell Creek (65.3 mg L^{-1}). The results indicate that the greater the stormflow, the greater the TSS concentration for each storm event sampled across both watersheds. TSS concentration was linearly and positively related to stormflow, with R^2 values ranging from 0.11 to 0.92 for all events in both watersheds. Across all sampling dates, the TSS concentration per unit stormflow was greater at Locust Stake than at Kimbell Creek, and was 7-fold greater at Locust Stake after the OHV trails were opened compared to when they were closed for maintenance and assessment. When the OHV trails were closed, the TSS concentration per unit stormflow was still significantly greater, by 4-fold, at Locust Stake compared to Kimbell Creek. Our results suggest that the presence and use of the Locust Stake OHV trail system are associated with poorer water quality, and with better water quality when the trails are closed. Forest managers face a well-defined set of tradeoffs between providing OHV recreation and water quality benefits that warrants careful planning and monitoring.*

Keywords. *National Forest System, Off-highway vehicles, Recreation, Sedimentation, Streamflow, Turbidity, Water quality.*

Off-highway vehicle (OHV) use is an increasingly popular outdoor recreational activity in the U.S., particularly in southern states. OHVs include four-wheel-drive automobiles, cross-country motorcycles, all-terrain vehicles, and other specially designed or modified off-road motor vehicles. Between 1993 and 2003, the estimated number of OHVs in the U.S. increased by 174%, surpassing eight million vehicles by the end of 2003 (Cordell et al., 2008). The number of persons above the age of 16 years participating in recreational OHV use also steadily increased after 1994; by spring 2016, 11.1 million households owned at least one OHV (Statista, 2016). OHV use peaked in 2008, with 13.3 million users participating in the activity, and gradually declined to present-day numbers (Statista, 2016). Recreational OHV trails are widely used in Georgia and surrounding states. In 2007, 33.7% of all OHV users (76,997,300) were residents of the southern U.S., and 3.1% of all participants (1,319,400) came from Georgia alone (Cordell et al., 2008). By 2012, 44% of all OHV sales were concentrated in the southern U.S. (Imlay, 2014).

Balancing the interest in OHV trail use with national directives to prevent undesirable environmental impacts introduces new challenges for managers of public land. OHV use can lead to a wide variety of environmental impacts (Ouren et al., 2007), including habitat degradation of stream pools (Chin, 2004), increased stream sedimentation (Riedel, 2006; Marion et al., 2014), and increased streambank erosion and downstream mud coatings (Marion et al., 2014). While some of these environmental effects can be reversed with trail closure, studies show that simply the presence of OHV trails, even when closed, is associated with decreased water quality (Marion et al., 2014). Soil compaction from past and current OHV use leads to decreased infiltration and greater surface runoff, and in turn can yield sediment input into streams (Iverson et al., 1981). Sediments eroded from trails are transported to nearby streams during storm events and for weeks after, where they are either suspended in the water column

Submitted for review in September 2018 as manuscript number NRES 13098; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in February 2019.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Chelcy F. Miniat,** Research Project Leader, and **Patsy P. Clinton,** Hydrologic Science Technician, USDA Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory, Otto, North Carolina; **Laren K. Everage,** Student, Department of Environment and Ecology, Institute for the Environment Program, University of North Carolina, Chapel Hill, North Carolina. **Corresponding author:** Chelcy Ford Miniat, Coweeta Hydrologic Lab, 3160 Coweeta Lab Rd., Otto, NC 28763; phone: 828-524-2128; e-mail: cfminiat@fs.fed.us.

or temporarily deposited along the streambed until the next event (Hamilton, 2002; Riedel, 2006).

Total suspended solids (TSS) concentrations in streams originating from OHV trails can impair water quality. During storm events, TSS concentrations are high due to the introduction of surface runoff and resuspension of streambed sediments. Throughout a storm event, TSS is greatest during the early part of a storm (i.e., the rising limb of the hydrograph) because this is when the majority of surface runoff contributes to stormflow in addition to resuspension of sediment stored in the streambed. Various studies have evaluated and recommended TSS concentrations and turbidity thresholds below which macroinvertebrate and fish communities are not negatively impacted; the turbidity threshold is 25 NTU, and the TSS thresholds range from 30 to 80 mg L^{-1} (NAS, 1972; Kundall and Rasmussen, 1995; Holmbeck-Pelham and Rasmussen, 1997; Walters et al., 2001). Land managers need information on the extent to which the presence and use of OHV trail systems affect TSS concentrations and turbidity levels in surface waters. In this study, we test those questions by investigating the water quality responses to the presence and use of OHV trails in a southern Appalachian forested watershed (the Locust Stake OHV trail system in Habersham County, Georgia, in the Chattahoochee National Forest) managed for multiple ecosystem services, including drinking water supply (Caldwell et al., 2014) and fishing.

The Locust Stake OHV trail system is in the North Fork of the Broad River basin in northern Georgia, which drains to the Savannah River basin. While the stream reach of the North Fork of the Broad River sampled in this study is not currently on the EPA 305(b)/303(d) impaired waters list (EPD, 2016), the stream has been listed on the impaired waters list previously for sediment (EPA, 2000), and concern over water quality and soil erosion in the OHV trail system has prompted land managers and stakeholder groups to reevaluate the impacts of the trail system on water quality. A study was conducted to evaluate acceptable total maximum daily loads (TMDLs) for sediment in this watershed following inclusion of the watershed on the 1998 impaired waters list (EPA, 2000). In that study, TSS concentrations were related to streamflow (i.e., sediment rating curves) for the impaired watershed and were evaluated against sediment rating curves for a reference watershed. TMDLs for the impaired watershed were recommended to stay within the 95% confidence interval of the sediment rating curve for the reference watershed.

In this study, we took a similar approach. Our objectives were to (1) determine the relationship between turbidity and TSS concentrations to aid in interpretation because state regulatory water quality standards are based on turbidity while federal standards are based on TSS, (2) determine the relationship between TSS concentrations for any given flow during storm events in watersheds with and without an OHV trail system, and (3) determine the relationship between TSS concentrations under closed versus open OHV trail system management. We hypothesized that for any given flow: (1) the TSS concentration would be greater in the watershed containing an OHV trail system compared to the reference watershed, and (2) the TSS concentration would be greater after trail opening compared to when the trails were closed.

Study Area and Methods

The study encompassed two watersheds within the Chattahoochee-Oconee National Forest, in Habersham and Stephens Counties, Georgia, and managed by the Chattooga River Ranger District as Locust Stake and Kimbell Creek (fig. 1). The climate is temperate, with warm humid summers, mild winters, and evenly distributed year-round precipitation. The long-term (120 years) average annual precipitation for a nearby site (~8 km, NCDC Historical NWS Station No. 098740, Toccoa, Ga.) is 1475 mm, mostly in the form of rain. Soils in both watersheds are primarily (35% to 43% of the watershed area) in the Madison-Louisa-Tallapoosa complex and are well-drained sandy loams on hills and side slopes. Grover and Madison fine sandy loam soils are also common in both watersheds (17% to 22% of the watershed area) and are well drained. Characteristic profiles of both complexes are fine sandy loams (0 to 15 cm) followed by clay to 75 cm and sandy clay loams from 75 to 90 cm. Parent material is a residuum weathered from mica schist and/or gneiss.

Locust Stake, the treatment watershed, is south-facing, 184 ha in area, 170 ha of which is managed by the Forest Service, and drains into the North Fork of the Broad River. The mean elevation is 440 m above mean sea level (msl). A mesic hardwood forest dominates lower elevations and transitions into a mixed pine-hardwood forest at higher elevations. A total of 4.8 km of paved roads, including two county roads and one U.S. highway, are located in the watershed (fig. 2). Road 301 is a permanently closed Forest Service road. This site also includes the Locust Stake OHV trail system, with eleven trails encompassing a total length of 14.8 km. Although no trails are mapped as crossing or fording streams, trails cross topographic depressions that connect to the drainage network and may experience surface runoff whenever rainfall is sufficient. Trail widths average between 1.5 and 2.4 m, while grades range between 0% and 45%, with most grades between 5% and 15% (Favro, 2012). The trails are open from March through December of each year but have the potential to close if more than 32 mm of rainfall is received within a 24 h period.

The trail system was developed in the mid-1980s from existing logging roads, and undesignated "user-created" OHV trails increased the number of trails in the system. Since the mid-1990s, concerns have arisen regarding the potential erosion and water quality impacts from repeated trail use. The trails remained open until 2012, when they were closed to assess environmental impact and conduct trail maintenance. During this period, a series of silt fences was installed in an attempt to control erosion. Loops A to F and a small section of loop G were reopened in 2014, offering 8 km of usable trail. These loops were closed again in December 2014 for routine maintenance and remained closed until 28 July 2016. Another 8 km of trail (including most of loop G) were permanently closed in 2014 to mitigate the severe erosion associated with OHV use (fig. 3). Before 2014, an estimated 3500 to 4500 visitors per year used the trail system, with hundreds more using the trails illegally. From its reopening on 28 July 2016 through 31 October 2016, 446 paid visitors, and an estimated 100 to 150 unpaid visitors

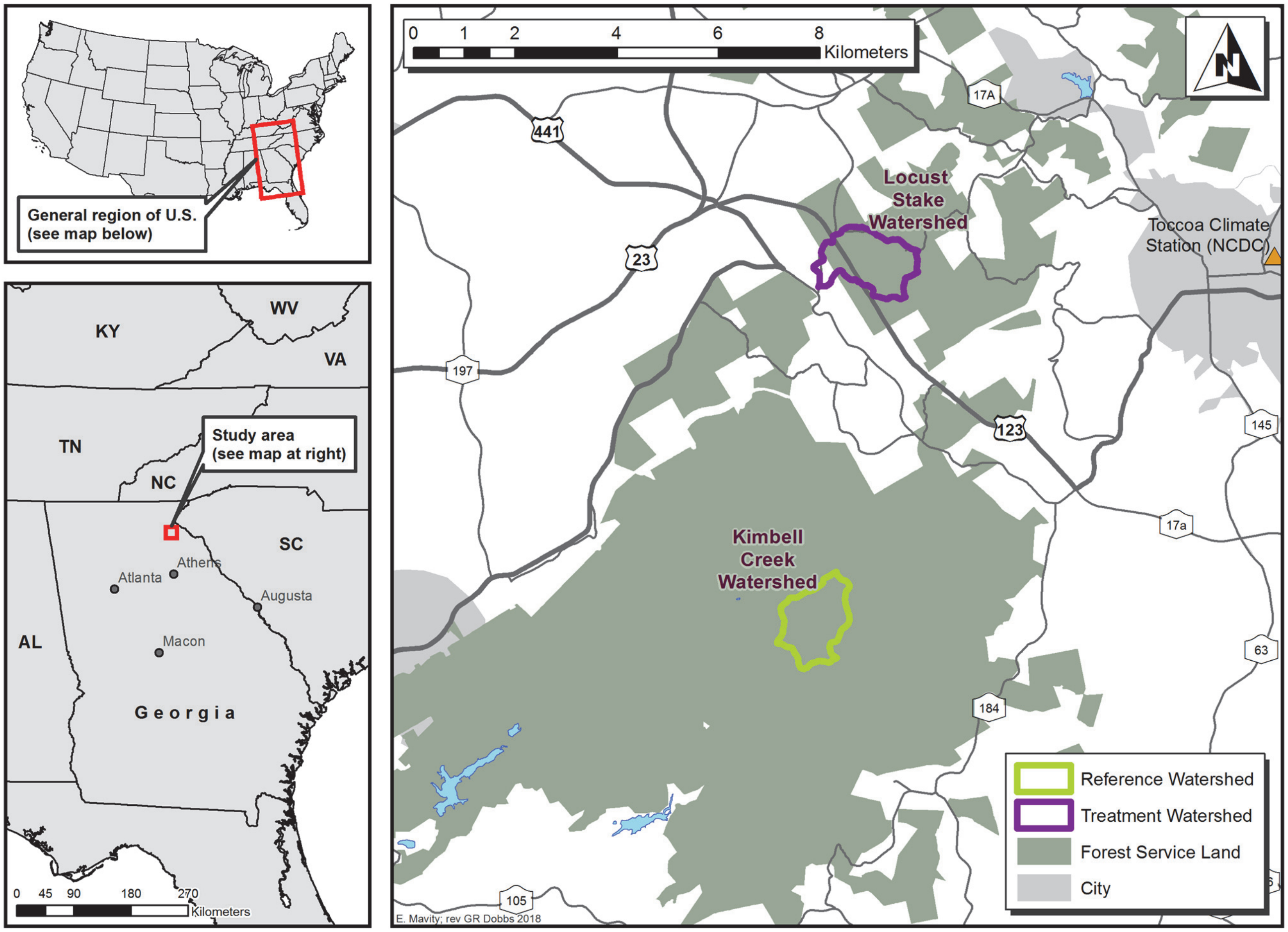

Figure 1. Location of study sites in northern Georgia (left). The Locust Stake and Kimbell Creek watersheds are within the Chattahoochee-Oconee National Forest (right). The NCDC Climate Station at Toccoa, Georgia, is also shown.

(P. Walrod, personal communication), used the OHV trail system.

The reference watershed (Kimbell Creek) is located approximately 12.9 km southwest of the treatment watershed. It is south-facing, 166 ha in area, with a mean elevation of 428 m above msl. Habitats within this watershed are generally sub-mesic, with mixed pine-hardwood forests in upland areas. This watershed does not include any OHV trails (fig. 4). Three gravel roads, totaling 1.3 km in length, are located in the watershed. Only one road, 0.4 km in length, is open to the public year-round. The other two roads are only seasonally open to public traffic. No roads cross or ford streams in the watershed.

Field Sampling

We collected flow-proportional water samples at both the reference and treatment sites using automated samplers (Teledyne, Inc.). The samplers were programmed to collect samples during heavy rainfall events when flow and TSS were potentially at their highest. The samplers were enabled when the streamflow stage rose 1.22 cm above its baseline elevation over a 1 h period. Samples, 1 L in volume, were collected every 10 min during each storm event, for up to 24 collections for a given storm. Stream stage was measured every 10 min in both storm and non-storm periods using a submerged probe pressure transducer on the automated sampler. We developed rating curves for each stream with transects co-located with the automated samplers to determine the stage-discharge relationship. Flow rate (Marsh-McBirney Flo-Mate 2000) and stream channel cross-sections were measured several times during the study period during different seasonal flow regimes to develop the rating curves. High flows were estimated using WinXSPRO, an interactive software package, along with the channel cross-section and slope measurements (Hardy et al., 2005).

The rating curve for Kimbell Creek followed a power function: $Q = 0.01982h^{3.0016}$ ($R^2 = 0.981$, $n = 30$, $p < 0.001$), where Q is flow in L s^{-1}, and h is stage in cm. The rating curve for Locust Stake also followed a power function: $Q = 0.36528h^{2.057}$ ($R^2 = 0.984$, $n = 20$, $p < 0.001$). Field equipment was installed, and sampling was initiated in February 2015 at Kimbell Creek and in June 2015 at Locust Stake, when the OHV trails were closed. Samples from each site were retrieved weekly until the end of the study (Oct. 2016, after the trails had opened) and were transported to the lab for analysis. Thus, each watershed was measured concurrently for TSS and flow for about four months.

Laboratory Measurements

We measured the TSS concentration for each water sam-

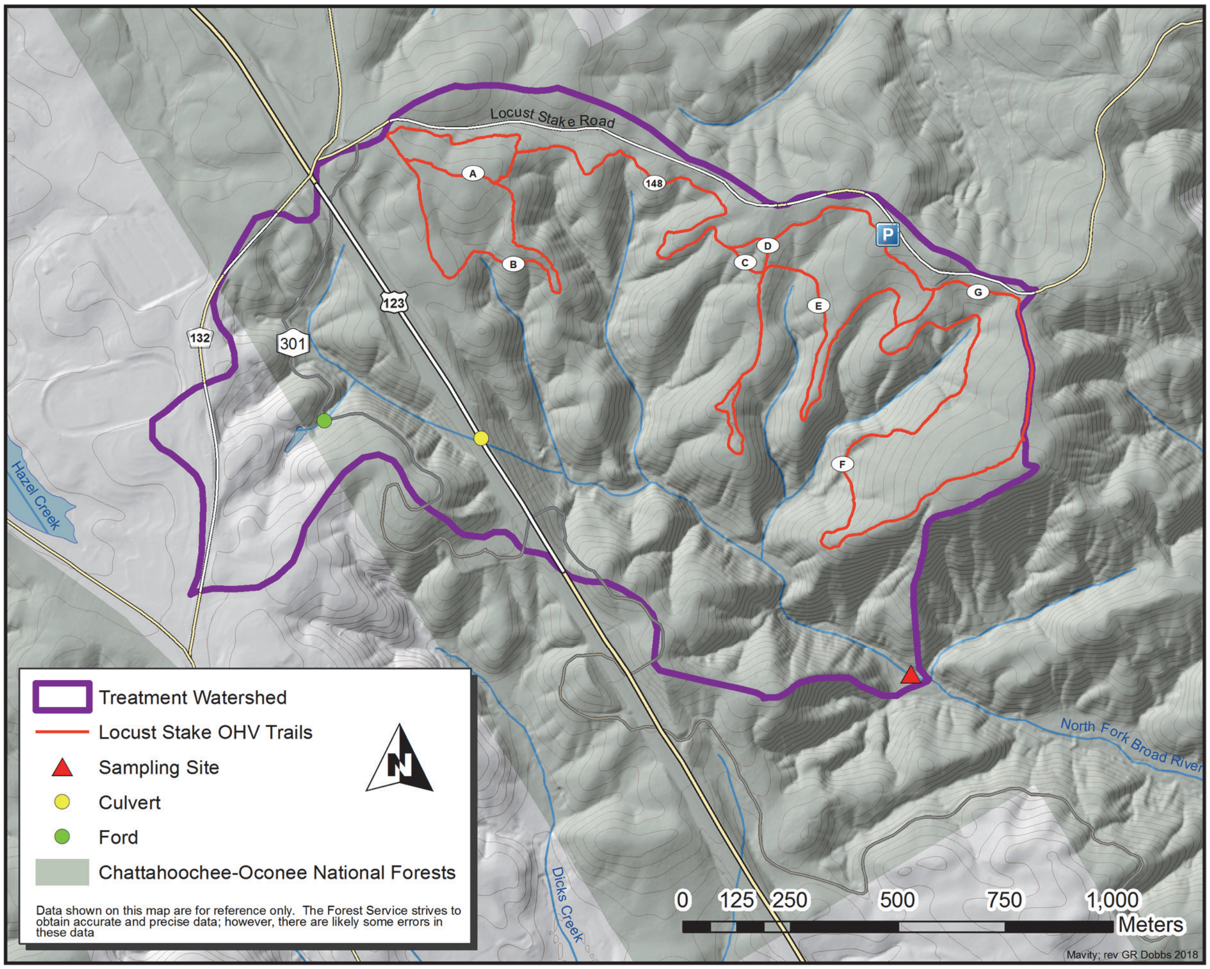

Figure 2. Locust Stake watershed, containing 14.8 km of off-highway vehicle (OHV) trails, was the treatment watershed. The water quality sampling site was located at the watershed outlet on the North Fork of the Broad River. The triangle denotes the automated sampler location. Trail loops are labeled A to G. Box P is the visitor parking area.

Figure 3. Two locations on the permanently closed section of loop G in the Locust Stake off-highway vehicle (OHV) trail watershed.

ple, and we also measured turbidity for a subset of samples. The TSS concentration was determined from the dry mass of solids filtered from a known volume of water. Filter papers (Whatman GF/C glass 1.5 microfiber, 5.5 cm) were rinsed with distilled deionized water, placed onto a vacuum pump (Millipore), and washed with 500 mL of deionized water. The filter papers were dried for 90 min at 125°C, and the dry mass was measured and recorded. Samples were then vigor-

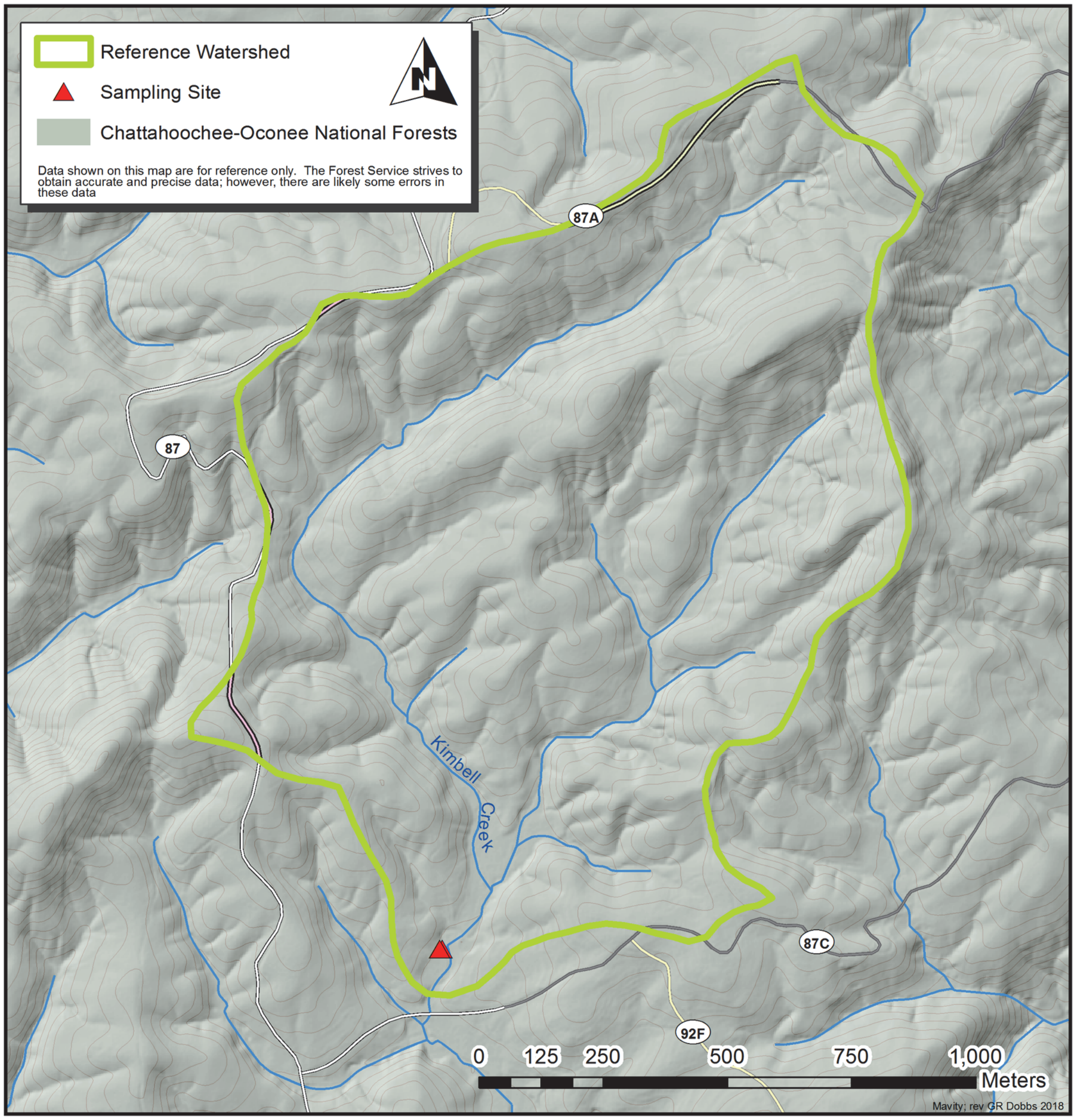

Figure 4. Kimbell Creek watershed was the reference watershed. The triangle denotes the automated sampler location.

ously agitated, the total volume was measured and recorded, and then the entire volume was filtered. If the turbidity measurement was high, only a 250 mL subsample was filtered. Filters with sediment residue were dried for 2.5 h at 105°C, and their mass was determined and recorded to the nearest 0.0001 g. For quality control purposes, blanks (n = 4) were also prepared and analyzed. TSS was determined as:

$$\mathrm{TSS} = (M_2 - M_1) / V \tag{1}$$

where TSS is total suspended solids (mg L^{-1}), M_1 is the dry mass (mg) of the empty filter paper, M_2 is the dry mass (mg) of the filter paper containing sediment particles, and V is the volume (L) of the filtered sample.

Turbidity (NTU) was measured (Hach 2100P) on a 15 mL subsample of each 1 L sample. Samples were gently agitated (inverted five to seven times) before measurement to resuspend the solids in the water. The sample cell was rinsed with deionized water between each use and wiped down with a lint-free cloth before each measurement to remove residue. We analyzed 65 and 95 samples from Kimbell Creek and Locust Stake, respectively, for both turbidity and TSS (table 1).

Experimental Design

We used a before-after control-impact (BACI) paired-watershed design (Stewart-Oaten et al., 1986). We compared water quality from Locust Stake and Kimbell Creek before and after OHV trail opening at the former site. The reference

Table 1. Sampling period, number of storm events, and number of samples collected for total suspended solids (TSS) concentration, turbidity, and stage at the off-highway vehicle (OHV) trail watershed (Locust Stake) and the reference watershed (Kimbell Creek).

Site	Collection Start Date	Collection End Date	No. of TSS Sampling Events	No. of TSS Samples Analyzed	No. of Stage Samples	No. of TSS and Turbidity Samples
Kimbell Creek (reference)	27 Feb. 2015	12 Oct. 2016	17	408	55,250	65
Locust Stake (OHV watershed)	27 Jun. 2015	12 Oct. 2016	23	552	52,615	95

watershed was closely located, geomorphically similar, and similar in area, soils, land cover, aspect, and elevation to the treatment watershed, but without the impact of OHV trail system presence and use.

Statistical Analysis

Linear regression was used to relate TSS concentration to turbidity for each watershed. For each storm event, we estimated the slopes of the sediment rating curves, i.e., TSS (mg L^{-1}) versus flow (L s^{-1}), and used these values as a response variable to adjust for differences in flow. This response variable was tested using analysis of variance (PROC GLM, SAS v. 9.4). Each storm was considered a replicate, as inference was restricted to these watersheds, and fixed factors included site (Locust Stake or Kimbell Creek) and time period (OHV trails closed vs. open). For all significant interactions, *post hoc* multiple comparison tests were performed (Tukey's HSD, $\alpha = 0.05$). Because our hypotheses were directional, all tests were one-tailed.

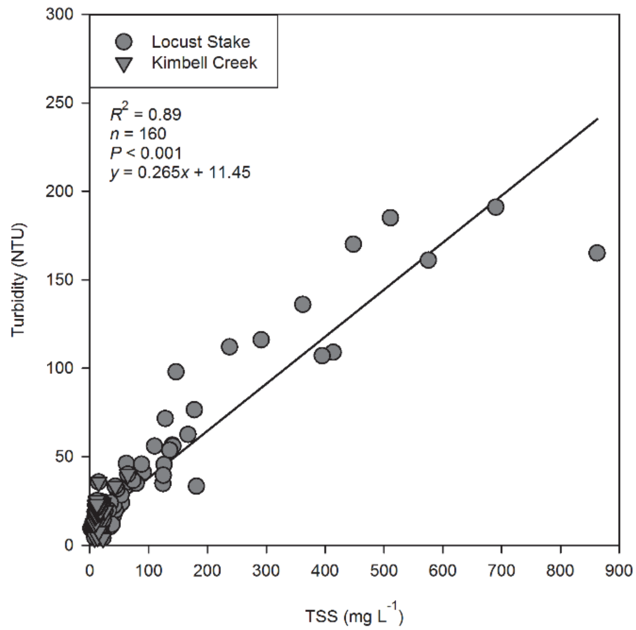

Figure 5. Relationship between turbidity and total suspended solids (TSS) concentration in stream water collected from Kimbell Creek (reference) and Locust Stake (OHV watershed).

Results

Within our sampling period, we were able to sample 17 and 23 storm events that produced a sustained rise in stream stage in the Kimbell Creek and Locust Stake watersheds, respectively. Approximately four sampling events were triggered for which a sustained rise in stage was not observed; these samples were excluded from analysis. Of the 23 storm events in Locust Stake, two were sampled after the OHV trails were opened on 28 July 2016. The low number of sampling events after the trails were opened was due to the uncharacteristically dry, late growing season. At a nearby gauge at the Coweeta Hydrologic Lab with long-term (1934 to present) precipitation records, data showed that 2016 was the sixth driest year on record (84 years), with a total of 1314 mm of precipitation. During September and October 2016, only 24 mm of rain was recorded over 61 days, making this period the driest two-month stretch on record, regardless of season (Miniat et al., 2017). Turbidity and TSS concentration had a strong, positive, linear relationship for the 160 samples collected for the two watersheds during the 17 and 23 storm events (fig. 5).

During the study period, the 10 min average flow rate across all sampling times was 19% greater, but the stormflow rates (average flow during TSS sampling events) were 29% lower, at Locust Stake compared to Kimbell Creek (fig. 6). At Kimbell Creek, the 10 min average flow rate across all sampling times was 470 L s^{-1}, and the average stormflow rate was 1147 L s^{-1}. At Locust Stake, the 10 min average flow rate across all sampling times was 561 L s^{-1} (fig. 6), and the average stormflow rate was 810 L s^{-1}. When adjusted for watershed area, the average flow rate across all sampling times was 0.25 m^3 s^{-1} km^{-2} at Locust Stake, compared to 0.33 m^3 s^{-1} km^{-2} at Kimbell Creek, and the stormflows were 0.44 and 0.69 m^3 s^{-1} km^{-2}, respectively.

For each storm event sampled across both watersheds, the greater the stormflow, the greater the TSS concentration. The TSS concentration was linearly and positively related to stormflow, with R^2 values ranging 0.12 to 0.92 for the 23 events in Locust Stake and from 0.11 to 0.91 for the 17 events in Kimbell Creek (fig. 7). Across all storms combined, the R^2 values were 0.64 for Locust Stake and 0.61 for Kimbell Creek. Across all sampling dates, the TSS concentration per unit stormflow was greater in Locust Stake than in Kimbell Creek, and was 7-fold greater in Locust Stake after the OHV trails were opened compared to when they were closed (site effect $F_{1,36} = 25.51$, $p < 0.001$; time period effect $F_{1,36} = 29.15$, $p < 0.001$; site × time period interaction, $F_{1,36} = 18.72$, $p < 0.001$, fig. 8). When the trails were closed, the TSS concentration per unit stormflow was still significantly greater (by 4-fold) at Locust Stake compared to Kimbell Creek.

Discussion

Our study evaluated streamflow, turbidity, and sediment discharge relationships in two forested watersheds that were similar in all physiographic and land use aspects, except one watershed had OHV trails and the other did not. We found that the suspended sediment concentration and turbidity for any given streamflow were greater in the watershed containing the OHV trail system, and both water quality parameters increased after the trails were opened. After the OHV trails were opened, TSS per unit stormflow increased more than 7-fold in the Locust Stake watershed, while a significant increase was not detected in the reference watershed. Thus, after adjusting for flows, the TSS concentration was greater in the watershed containing the OHV trail system after trail opening compared to when trails were closed, confirming our hypotheses.

Sediment concentrations are typically low during low flow conditions and increase during storm events (Dunne and Leopold, 1978). This is due to the increased power of the stream to move sediment during higher flow conditions,

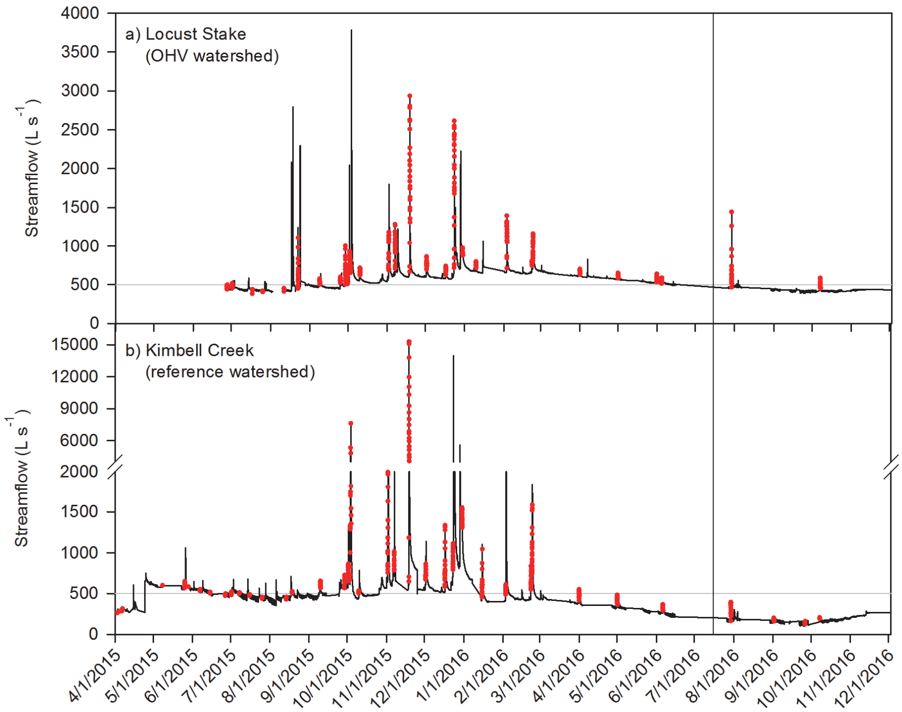

Figure 6. Time series of streamflow from (a) Locust Stake and (b) Kimbell Creek. Red symbols denote auto-sampling of stream water for TSS determination. After 28 July 2016 (vertical line), the OHV trails in the Locust Stake watershed were opened for public use. Before that date, the trails were closed. The gray horizontal line at 500 L s^{-1} is shown for reference. Occasionally, a storm was not sampled due to battery failure.

as well as additional sources of sediment from overland flow contributing to streams. During the course of a storm, TSS concentrations are typically greater for any given flow during the rising limb of the hydrograph compared to the falling limb, representing the mobilization of sediment stored on the streambed. Studies typically use a log-log relationship to describe this TSS versus discharge relationship, as the goal of many of these studies is to construct a predictive sediment rating curve across the full flow range for a stream, and log transforming reduces the apparent variation (Asselman, 2000; Horowitz, 2003). Horowitz (2003) discussed the effect of temporal variation on sediment rating curves and how log-log relationships underpredict TSS from large storm events and overpredict TSS from small storm events. To address this, some studies have constructed sediment rating curves for different seasons or flow regimes to improve predictions (e.g., Walling, 1977).

We chose to use a linear relationship between discharge and TSS for two reasons. First, we analyzed each storm event, and at this scale, the fit was as good as or better than a log-log or a log-linear relationship. Second, our goal was only to test whether or not, across the sampled events, the individual storm TSS versus discharge slopes were greater in the watershed containing OHV trails compared to the reference watershed, as opposed to constructing a predictive relationship across all possible events. Because a relationship was constructed for each event, rather than combining all possible events, our data had relatively high R^2 values compared to other studies that combined all events (e.g., Reid and Dunne, 1984). For example, Clinton and Vose (2006) found that TSS concentration was less under baseflow and greater under stormflow (2.84 and 11.66 mg L^{-1}) for a nearby reference forested site in the Chattooga River watershed, but their TSS concentration and stormflow relationships were relatively weak (adjusted $R^2 = 0.13$). In another study in the Chattooga River watershed, Riedel et al. (2003) also found a weak relationship between TSS and discharge, ranging from non-significant to $R^2 = 0.37$. However, a third study in the Chattooga River watershed found strong positive relationships between TSS and streamflow (Pruitt, 1999; Pruitt et al., 2001), and these relationships formed the basis of the TMDLs for the North Fork of the Broad River (EPA, 2000).

Sediment delivery to streams can depend on land cover and land use. For this region, in general, the greater the forest cover, the lower the TSS concentration in stream water (Bolstad et al., 2006). Within forested watersheds, land use can also play a significant role in stream sediment concentrations. For example, skidding and roads associated with forest harvesting operations can deliver large amounts of sediment to streams. Aust et al. (2011) estimated soil loss rates for 32 ford crossings in Appalachian forests undergoing harvesting and found rates ranging between 31 and 42 tonnes ha^{-1} year^{-1}. Other estimates of soil loss from bare soil due to harvesting operations ranged between 24 and 138 tonnes ha^{-1} year^{-1} (Sawyers et al., 2012; Wade et al., 2012; Wear et al., 2013). Non-motorized recreational trails that cross streams can also deliver sediment to streams. Kidd et al. (2014) found that 5 to 15 tonnes ha^{-1} year^{-1} of sediment could be delivered to streams from non-motorized recreational trails. Lastly, while erosion rates can seem much greater from soil disturbances associated with timber harvesting operations compared to recreational land uses, such as OHV trails, harvesting operations can be short-lived relative to the perennial nature of recreational trails, and thus may result in

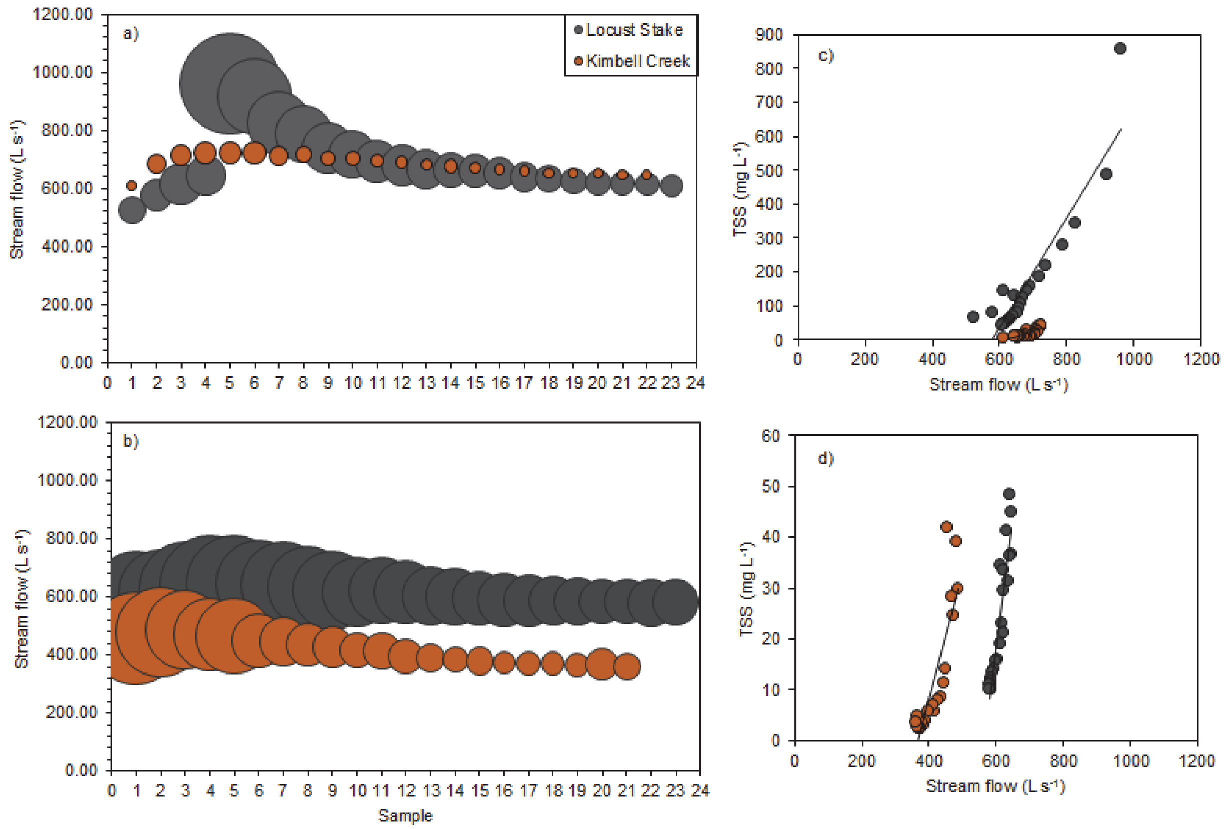

Figure 7. Stormflow for two sampling events during (a) 30 April 2016 and (b) 29 September 2015 for Kimbell Creek (reference) and Locust Stake (OHV watershed) when the OHV trails were closed. These two events were chosen to represent the most frequent storm size and time periods with relatively low (September) and high (April) soil moisture storage conditions. Symbol size represents the TSS value (mg L^{-1}) for each 15 min sample (i.e., *x*-axis represents 6 h of sampling). Graphs (c) and (d) show the TSS values and linear relationships between stormflow and TSS.

lower long-term average erosion rates.

Both the presence and the recentness of trail use affected sediment concentration. The TSS concentration per unit stormflow was lower in the reference watershed compared to the OHV watershed, even when the trails were not in use. Our TSS sampling in the OHV watershed during trail closure failed to capture the largest storm event (fig. 6), and this likely underestimated the upper limit of TSS concentration in this watershed. Our approach of comparing TSS concentration per unit stormflow likely was not affected by missing this sampling event, aside from reducing our statistical power, as we still detected significantly greater TSS concentration per unit stormflow in the OHV watershed compared to the reference watershed. Previous work by Foltz (2006) and Marion et al. (2014) concluded that OHV trails, regardless of current use, increase sediment deposition near trail crossings. After the trails were opened, the amount of TSS per unit streamflow increased by 7-fold in the OHV watershed compared to when the trails were closed. This suggests that the recentness of OHV use increases sediment delivery to adjacent streams. Previous research also showed that OHV use can increase sediment deposition into in-stream pool habitats, such as lateral-scour pools, mid-channel pools, and step pools, and can lead to decreased pool depth and volume in watersheds with open trail systems (Chin, 2004).

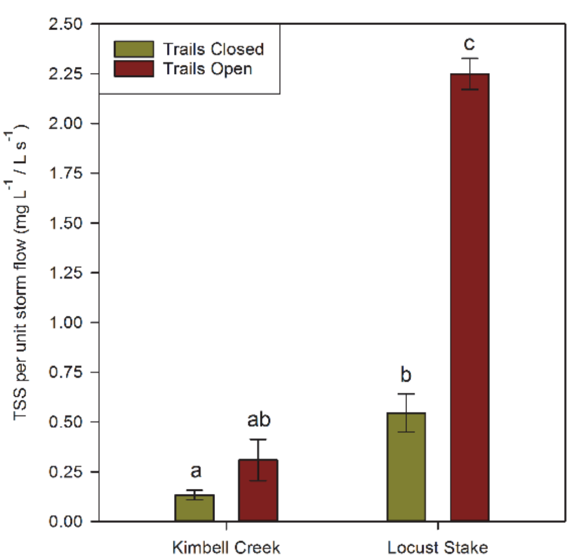

Figure 8. Mean slopes of linear relationships (mg L^{-1}/L s^{-1}) for TSS versus stormflow for all sampling events at Kimbell Creek (reference) and Locust Stake (OHV watershed) when the OHV trails were closed prior to 28 July 2016 and after the trails were opened. Error bars denote standard errors. Different letters indicate statistically different means. Figures 7c and 7d show the linear relationships for which these slopes were determined.

While this study is an important first step in testing whether the presence and use of OHV trails negatively impact water quality, our results should be considered within the limitations and strengths of the study. Our study had limited sampling (two events) after the trails were opened. Sampling during trail opening occurred during a historically dry period, which did not allow us to sample flows that were as high as when the trails were closed. Despite this, the slope of the sediment rating curve increased by 7-fold and was certainly outside the 95% confidence interval of the sediment rating curve for the reference watershed. Our inference space is limited in scope to these watersheds, rather than all OHV-containing forested watersheds in general, as we did not have replicates at this scale of inference. We also did not determine the source of sediment delivery to these streams, the influence or contribution of legacy sediment or bedload on TSS and turbidity, nor whether the TSS was organic or mineral. Future work to characterize the volatile (or non-mineral) solids in the TSS samples would aid in interpretation. Strengths of our study include the duration of sampling for the entire study and sampling under both high-flow and low-flow conditions. We also used a paired-watershed approach, with a before and after event (trails closed vs. open). This design allowed us to control for climatic effects and isolate the factors of interest (trail presence and use).

Our results suggest that OHV trails or access roads to the trails may be a significant source of sediment in streams during storms when overland flow on the trails is occurring, and may be the cause of degraded water quality because the presence and recentness in use of OHV trails were the main differences between the paired watersheds and time periods. Similar to other southern Appalachian loamy mountain soils, the well-drained sandy loams on the hills and side slopes in both watersheds are highly erodible when exposed but have minimal erosion yields when well covered with vegetation (Van Lear et al., 1997). Steps taken to permanently cover bare soils in the Locust Stake watershed would likely improve water quality, even for trails that have been closed and are not in use. Steps taken to reduce, or eliminate, trail use would also likely improve water quality. If trail use, to some degree, continues, installing vegetative buffers at all trail crossings at the end of the use season, eliminating ford crossings, minimizing the number of crossings, and installing sediment traps would likely reduce the TSS concentration and turbidity in the stream. All of these actions present maintenance challenges and expenses, but they would allow the OHV trail system to be used. Forest managers face a well-defined set of tradeoffs between providing OHV recreation and water quality benefits that warrants careful planning and monitoring (Issa, 2003).

Conclusion

Our study showed that the presence and use of the Locust Stake OHV trail system increased sediment concentration and turbidity in the North Fork of the Broad River compared to a nearby reference watershed that was similar in vegetation, soils, elevation, and aspect. These effects were reflected in greater TSS concentrations per unit stormflow when compared to the reference watershed. Our results suggest that the presence and use of the Locust Stake OHV trail system are associated with poorer water quality, and with better water quality when the trails are closed.

Acknowledgements

Joint funding for this project was from the USDA Forest Service, Southern Research Station, Coweeta Hydrologic Lab, and the USDA Forest Service, Chattooga River Ranger District. We acknowledge the help of many individuals who were critical to the completion of this project: Phillip Walrod, Stephanie Laseter, Erika Mavity, Brett Sparks, Matt Rushton, Blaine Boydston, Shaun Parker, Sergio Olivera, Katie Bower, Randy Fowler, Cindi Brown, Brandon Welch, Sheila Gregory, Carol Harper, Ed Hunter, Jill Davis Belanger, Ryan Foote, Rebecca Dobbs, and Jason Engle. Drs. James Costa and Sarah Workman at the Highlands Biological Station provided helpful support to L. K. Everage on this project. We thank Drs. J. M. Grace, D. Marion, D. N. Wear, and three anonymous reviewers for their comments on the manuscript.

References

Asselman, N. (2000). Fitting and interpretation of sediment rating curves. *J. Hydrol., 234*(3-4), 228-248. https://doi.org/10.1016/S0022-1694(00)00253-5

Aust, W. M., Carroll, M. B., Bolding, M. C., & Dolloff, C. A. (2011). Operational forest stream crossings effects on water quality in the Virginia Piedmont. *South. J. Appl. For., 35*(3), 123-130.

Bolstad, P., Jenks, A., Riedel, M., & Vose, J. M. (2006). Estimating sediment yield in the southern Appalachians using WCS-SED. *Proc. Joint Federal Interagency Conf., Interdisciplinary Solutions for Watershed Sustainability* (pp. 136-143). Reston, VA: U.S. Geological Survey.

Caldwell, P., Muldoon, C., Miniat, C. F., Cohen, E., Krieger, S., Sun, G., ... Bolstad, P. V. (2014). Quantifying the role of National Forest system lands in providing surface drinking water supply for the southern United States. Gen. Tech. Report SRS-197. Asheville, NC: U.S. Forest Service, Southern Research Station. Retrieved from https://www.fs.usda.gov/treesearch/pubs/47706

Chin, A. R., Deven, M., Marion, D. A., & Clingenpeel, J. A. (2004). Effects of all-terrain vehicles on stream dynamics. Gen. Tech. Report SRS-74. Asheville, NC: U.S. Forest Service, Southern Research Station.

Clinton, B. D., & Vose, J. M. (2006). Variation in stream water quality in an urban headwater stream in the southern Appalachians. *Water Air Soil Pollut., 169*(1-4), 331-353. https://doi.org/10.1007/s11270-006-2812-x

Cordell, H. K., Betz, C. J., Green, G., & Owens, M. (2008). Off-highway vehicle recreation in the United States and its regions and states: An update national report from the National Survey on Recreation and the Environment (NSRE). Asheville, NC: U.S. Forest Service, Southern Research Station. Retrieved from https://www.fs.fed.us/recreation/programs/ohv/IrisRec1rpt.pdf

Dunne, T., & Leopold, L. B. (1978). Sediment production and transport. In *Water in environmental planning* (pp. 661-686). San Francisco, CA: W.H. Freeman.

EPA. (2000). Total maximum daily load (TMDL) development for sediment in the north fork of the Broad River watershed. Atlanta, GA: U.S. Environmental Protection Agency.

EPD. (2016). 305(b)/303(d) List of waters. Atlanta, GA: Georgia Department of Natural Resources, Environmental Protection Division. Retrieved from https://epd.georgia.gov/georgia-305b303d-list-documents

Favro, J. (2012). Locust Stake ATV trail system inventory, assessment, and management plan. Atlanta, GA: U.S. Forest

Service, Southern Region. Retrieved from https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5382439.pdf

Foltz, R. B. (2006). Erosion from all-terrain vehicle (ATV) trails on National Forest lands. ASABE Paper No. 068012. St. Joseph, MI: ASABE.

Hamilton, L. J. (2002). A study of the effects of ORV stream crossings on water quality of two streams located in the Angelina National Forest, Texas: A physicochemical and benthic macroinvertebrate analysis. MS thesis. Nacogdoches, TX: Stephen F. Austin State University.

Hardy, T., Panja, P., & Mathias, D. (2005). WinXSPRO, A channel cross-section analyzer, user's manual, ver. 3.0. Gen. Tech. Report RMRS-GTR-147. Fort Collins, CO: U.S. Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-147

Holmbeck-Pelham, S. A., & Rasmussen, R. C. (1997). Characterization of temporal and spatial variability of turbidity in the upper Chattahoochee River. In K. J. Hatcher (Ed.), *Proc. Georgia Water Resources Conf.* (pp. 144-147). Athens, GA: University of Georgia.

Horowitz, A. J. (2003). An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrol. Proc., 17*(17), 3387-3409. https://doi.org/10.1002/hyp.1299

Imlay, M. (2014). Utility task vehicles by the numbers. Diamond Bar, CA: Specialty Equipment Market Association. Retrieved from https://www.sema.org/sema-news/2014/07/utility-task-vehicles-by-the-numbers

Issa, B. A. (2003). Development of guidance and evaluation criteria for off-highway vehicle (OHV) management planning. MS thesis. Eugene, OR: University of Oregon, Department of Planning, Public Policy, and Management.

Iverson, R. M., Hinckley, B. S., Webb, R. M., & Hallet, B. (1981). Physical effects of vehicular disturbances on arid landscapes. *Science, 212*(4497), 915-917. https://doi.org/10.1126/science.212.4497.915

Kidd, K. R., Aust, W. M., & Copenheaver, C. A. (2014). Recreational stream crossing effects on sediment delivery and macroinvertebrates in southwestern Virginia, USA. *Environ. Mgmt., 54*(3), 505-516. https://doi.org/10.1007/s00267-014-0328-5

Kundall, J. E., & Rasmussen, R. C. (1995). Erosion and sedimentation: Scientific and regulatory issues. Developed for the Georgia Board of National Resources. Georgia Board of Regent's Scientific Panel on Evaluating the Erosion Measurement Standard defined by the Georgia Erosion and Sedimentation Act.

Marion, D. A., Phillips, J. D., Yocum, C., & Mehlhope, S. H. (2014). Stream channel responses and soil loss at off-highway vehicle stream crossings in the Ouachita National Forest. *Geomorphology, 216*, 40-52. https://doi.org/10.1016/j.geomorph.2014.03.034

Miniat, C. F., Laseter, S. H., Swank, W. T., & Swift, L. W. (2017). Daily precipitation data from recording rain gages (RRG) at Coweeta Hydrologic Lab, North Carolina. Fort Collins, CO: U.S. Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2017-0031

NAS. (1972). Water quality criteria 1972: A report of the committee on water quality criteria. Washington, DC: National Academy of Science and National Academy of Engineering.

Ouren, D. S., Haas, C., Melcher, C. P., Stewart, S. C., Ponds, P. D., Sexton, N. R., ... Bowen, Z. H. (2007). Environmental effects of off-highway vehicles on Bureau of Land Management lands: A literature synthesis, annotated bibliographies, extensive bibliographies, and internet resources. USGS Open-File Report 2007-1353. Reston, VA: U.S. Geological Survey.

Pruitt, B. (1999). Chattooga River watershed hydrologic/sedimentation study. Athens, GA: U.S. Environmental Protection Agency, Region 4.

Pruitt, B., Melgaard, D. L., Howard, H., Flexner, M. C., & Able, A. S. (2001). Chattooga River watershed ecological/sedimentation project. *Proc. Federal Interagency Sedimentation Conf.* Reston, VA: U.S. Geological Survey.

Reid, L. M., & Dunne, T. (1984). Sediment production from forest road surfaces. *Water Resour. Res., 20*(11), 1753-1761. https://doi.org/10.1029/WR020i011p01753

Riedel, M. S. (2006). Quantifying trail erosion and stream sedimentation with sediment tracers. *Proc. 2nd Interagency Conf. on Research in the Watersheds.* Asheville, NC: U.S. Forest Service, Southern Research Station. Retrieved from https://www.fs.usda.gov/treesearch/pubs/28852

Riedel, M. S., Vose. J., M., & Leigh, D. S. (2003). The road to TMDL is paved with good intentions: Total maximum daily loads for a wild and scenic river in the southern Appalachians. *Proc. Total Maximum Daily Load (TMDL) Environmental Regulations II Conf.* (pp. 356-366). St. Joseph, MI: ASABE. https://doi.org/10.13031/2013.15582

Sawyers, B. C., Bolding, M. C., Aust, W. M., & Lakel, W. A. (2012). Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia Piedmont. *J. Soil Water Cons., 67*(4), 300-310. https://doi.org/10.2489/jswc.67.4.300

Statista. (2016). Number of people living in households that own an ATV (all-terrain vehicle) in the United States from spring 2008 to spring 2016 (in millions). New York, NY: Statista, Inc. Retrieved from http://www.statista.com

Stewart-Oaten, A., Murdoch, W. W., & Parker, K. R. (1986). Environmental impact assessment: "Pseudoreplication" in time? *Ecology, 67*(4), 929-940. https://doi.org/10.2307/1939815

Van Lear, D. H., Taylor, G. B., & Hansen, W. F. (1997). Sediment sources to the Chattooga River. *Proc. 9th Biennial Southern Silviculture Conf.* (pp. 357-362). Gen. Tech. Report SRS-20. Asheville, NC: U.S. Forest Service, Southern Research Station.

Wade, C. R., Bolding, M. C., Aust, W. M., Lakel III, W. A., & Schilling, E. B. (2012). Comparing sediment trap data with the USLE-Forest, RUSLE2, and WEPP-Road erosion models for evaluation of bladed skid trail BMPs. *Trans. ASABE, 55*(2), 403-414. https://doi.org/10.13031/2013.41381

Walling, D. E. (1977). Assessing the accuracy of suspended sediment rating curves for a small basin. *Water Resour. Res., 13*(3), 531-538. https://doi.org/10.1029/WR013i003p00531

Walters, D. M., Freeman, M. C., Leigh, D. S., Freeinan, B. J., Paul, M. J., & Pringle, C. M. (2001). Bed texture and turbidity as indicators of fish biotic integrity in the Etowah River System. *Proc. Georgia Water Resources Conf.* (pp. 233-236). Atlanta, GA: Georgia Water Resources Institute.

Wear, L. R., Aust, W. M., Bolding, M. C., Strahm, B. D., & Dolloff, C. A. (2013). Effectiveness of best management practices for sediment reduction at operational forest stream crossings. *Forest Ecol. Mgmt., 289*, 551-561. https://doi.org/10.1016/j.foreco.2012.10.035