MONITORING SEDIMENT PRODUCTION FROM FOREST ROAD APPROACHES TO STREAM CROSSINGS IN THE VIRGINIA PIEDMONT

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Abstract--Reopening of abandoned legacy roads is common in forest operations and represents a reduced cost in comparison to new road construction. However, legacy roads may have lower road standards and require additional best management practice (BMP) implementation upon reopening to protect water quality. Silt fences and elevation measurements of trapped sediment were used to quantify annual sediment delivery rates for reopened bare and existing gravel forest road approaches to stream crossings in the Virginia Piedmont. Additionally, rainfall simulation experiments were performed on reopened legacy road stream crossing approaches to quantify the cost-effectiveness of a range of gravel surface coverage for control of total suspended solids (TSS) concentration from road surface runoff during storm events. In the sediment trap study, mean annual sediment delivery for the reopened bare approaches (98 Mg ha^{-1} $year^{-1}$) was 7.5 times greater than that of the gravel approaches (13 Mg ha^{-1} $year^{-1}$). Problem road approaches were associated with inadequate water control (greater than 75 m between water control structures) and 90 to 100 percent bare soil conditions throughout the year. Median TSS concentration of road surface runoff (g L^{-1}) for the Bare treatment rainfall simulations (2.34 g L^{-1}; 90 to 100 percent bare soil conditions) was 1.8 times greater than Gravel 1 (1.32 g L^{-1}; 25 to 50 percent gravel surface coverage) and 3.3 times greater than Gravel 2 (0.72 g L^{-1}; 50 to100 percent gravel surface coverage). Gravel surfacing of the road approaches cost $10.27/m of road length for a gravel depth of 7.6 cm and local cost of $27.78/Mg ($25 per ton).

INTRODUCTION

Nonpoint sources of stream sedimentation associated with forest operations include forest roads, skid trails, and log decks (Anderson and Lockaby 2011, Croke and Hairsine 2006, Grace 2005). Forest road stream crossings and their associated approaches (i.e., the section of road above and directly connected to the stream crossing) represent erosion sources with the greatest potential for sediment delivery because of nearly direct hydrologic connectivity with streams (Aust and others 2011, Lane and Sheridan 2002, Wear and others 2013). Additionally, stream crossing construction and maintenance involves excavation and fill work with heavy machinery often directly in the stream channel. Excessive stream sedimentation degrades water quality and aquatic habitat (Goode and others 2012, Robinson and others 2010), and protection of water quality is the primary function of forestry best management practices (BMPs) (Aust and Blinn 2004). However, the cost of extensive BMP implementation can be substantial (Shaffer and others 1998). Thus, it is critical to quantify the cost-efficacy of BMPs for forest operations, especially those that represent direct pathways and primary sources of sediment to stream channels (i.e., forest road stream crossings and their associated approaches).

Forest roads provide access for timber harvesting, hazardous fuel reduction efforts, and woody biomass utilization for energy. Reopening of abandoned legacy roads is cheaper than new road construction (Foltz and others 2009), but legacy road construction commonly occurred prior to the BMP era, which has improved standards for water quality protection through the use of proper planning for road location, as well as the management of road grade, stormwater runoff, and erosion and sediment delivery. Upon reopening, legacy roads may require additional BMPs to protect water quality, especially if roads are steep, bare, and have inadequate water control.

Nationwide, forest road sediment delivery to stream channels poses issues for water quality and aquatic habitat degradation (Goode and others 2012, Robinson and others 2010), which is underscored by the 2012 U.S. Supreme Court consideration of the Ninth Circuit Court ruling that was initiated by NEDC versus Brown. The Ninth Circuit ruling stated that roadside ditches are point sources, requiring a National Pollution Discharge Elimination System (NPDES) permit, if they collect and deposit stormwater into the surface waters of the U.S. (Boston 2012). The U.S. Supreme Court decision retained the nonpoint source pollution (NPSP) status of forest roads and silvicultural exemptions by reversing the Ninth Circuit ruling in March 2013, but further litigation is likely until legislation clarifies the NPSP status of forest roads.

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Nevertheless, it is clear that improved cost-effectiveness and implementation of forest road BMPs are critical for water quality protection.

Two field studies were recently completed in the Virginia Piedmont that addressed the effectiveness of forest road stream crossing approach BMPs. The objectives of the first study were to: (1) use sediment traps to measure annual rates of sediment delivery from forest road approaches to stream crossings due to road reopening in the Virginia Piedmont, (2) compare sediment delivery rates of reopened bare road approaches with existing graveled road approaches, and (3) identify the major road approach characteristics above the stream crossing that govern rates of sediment delivery. The objective of the second study was to evaluate the sediment reduction and cost efficacy of partial and complete graveling of road approaches.

MATERIALS AND METHODS

Study Sites

Fifteen southwestern Virginia Piedmont forest road approaches to stream crossings were selected for study of sediment delivery at the Reynolds Homestead Forest Resources Research Center (RHFRRC), located in Critz, VA (Patrick County). Topography is characterized by rolling hills, with side slopes generally ranging from 8 to 25 percent and a mean elevation of approximately 335 m above mean sea level (NRCS 2013). Mean annual rainfall is 1250 mm, with a mean snow contribution of 270 mm to the total precipitation. Mean air temperature ranges from a low of -1.8 °C in January to a high of 29.7 °C in July (Sawyers and others 2012). The predominant soil series is Fairview sandy clay loam (fine, kaolinitic, mesic typic Kanhapludults). Soil parent material is residuum from mica schist and mica gneiss. Soils are characterized as being moderately eroded and well drained (NRCS 2013), but road construction and traffic can result in soils with reduced infiltration capacity on the running surface. Kadak (2012, unpublished data) used double-ring infiltrometers to measure infiltration rates for six reopened stream crossing approaches at RHFRRC. Infiltration rates ranged from 0.06 to 0.72 cm hour^{-1}. In addition, the severe erosion hazard rating for forest roads and trails at RHFRRC (NRCS 2013) underscores the importance of pre-harvest planning to control road grade, minimize stream crossings, and implement BMPs to minimize erosion and sediment delivery. As is typical of the Piedmont region, old agricultural gullies are common because most of the contemporary forested watersheds were formerly in agriculture during the 1800s (Trimble 1974).

Site Survey

In July 2011, a total station (Sokkia total station model SET-520, Tokyo, Japan) was used to measure the length of the road approaches to stream crossings. Length was defined as the distance between the nearest water control structure (i.e. water bar, turnout, or rolling or broad-based dip) and the stream. Road approach slope and mean width of the road (running surface plus ditch, if applicable) were also quantified during the total station survey (table 1).

Treatments

Two different methods were used to quantify sediment delivery and evaluate gravel surfacing BMPs for forest road approaches to stream crossings: (1) a forest operational approach that used silt fences and monthly elevation measurements of trapped sediment to quantify sediment delivery associated with existing graveled road approaches and reopened bare legacy road approaches to stream crossings, and (2) an experimental approach that used rainfall simulation experiments to quantify the cost-effectiveness of a range of gravel surface coverage for control of total suspended solids (TSS) concentration from road surface runoff during storm events.

Sediment trap study--Five road segments were bladed with a bulldozer in late July 2011, creating initial conditions of 100 percent bare soil, to simulate sediment delivery from reopening abandoned legacy roads. Two of the road segments represented road approaches to a 1970s-era abandoned skidder crossing resembling an earthen dam. The remaining three road segments represented sections that

Table 1--Site physical characteristics of the sediment trap and rainfall simulation road approach study plots. Multiple segments within a study plot indicate a break in road grade

Study sites segment ID	Crossing type	Length	Surface width	Slope	Vertical slope	Soil texture
		------------*m*------------		%		
Sediment trap						
Gravel 1,2	Culvert	29.0	3.2	10.0	Linear	Sandy clay loam
Gravel 1,1	-	11.0	3.0	12.0	Linear	Sandy clay loam
Gravel 2	Culvert	24.4	3.4	4.0	Linear	Sandy clay loam
Gravel 3,1	Culvert	12.5	3.4	2.0	Linear	Sandy clay loam
Gravel 3,2	-	39.3	2.7	6.7	Concave	Sandy clay loam
Gravel 4,1	Culvert	9.8	4.5	14.3	Linear	Silt loam
Gravel 4,2	-	31.7	5.2	19.0	Concave	Silt loam
Bare 1	Earth dam	21.0	2.4	21.0	Convex	Clay loam
Bare 2	Earth dam	10.0	2.1	19.0	Concave	Silty clay loam
Bare 3,2	-	19.5	2.7	14.3	Concave	Silty clay loam
Bare 3,1	-	22.6	2.1	13.5	Linear	Silty clay loam
Bare 4	-	129.5	3.0	3.9	Linear	Loamy sand
Bare 5	-	75.1	2.4	4.0	Linear	Silty clay loam
Rainfall simulation						
Crossing 1 right,2	Ford	12.7	4.0	13.5	Concave	Sandy clay loam
Crossing 1 right,1	-	13.1	3.4	5.4	Linear	Sandy clay loam
Crossing 1 left,1	-	9.6	3.0	1.3	Linear	Sandy clay loam
Crossing 1 left,2	-	31.7	2.4	5.7	Concave	Sandy clay loam
Crossing 2 right	Ford	19.2	3.2	13.7	Convex	Sandy clay loam
Crossing 2 left,1	-	19.5	2.4	14.9	Concave	Sandy clay loam
Crossing 2 left,2	-	15.8	2.9	16.0	Linear	Sandy clay loam
Crossing 3 right,2	Ford	29.0	3.8	15.0	Concave	Sandy clay loam
Crossing 3 right,1	-	10.6	2.6	19.1	Linear	Sandy clay loam
Crossing 3 left,1	-	10.0	2.2	6.5	Linear	Clay loam
Crossing 3 left,2	-	13.5	3.3	6.3	Linear	Clay loam

were not immediately connected to stream channels. Where cut and fill road profiles existed, in-sloping and outboard edge berm installation were used to redirect all runoff and sediment to the base of the plot, where silt fences were installed across the entire width of the running surface (and ditch, if applicable) to trap all sediment from the road prism, similar to the method suggested by Robichaud and Brown (2002) (fig. 1). Silt fences were also installed at the base of three culvert crossing approaches on a graveled road that was constructed in November 2010. Finally, silt fences were installed at the base of a legacy gravel road approach to a culvert crossing that was reshaped with a bulldozer blade and re-graveled. Reshaping included in-sloping to the cutbank on the backslope portion of the hillslope and crowning at the toeslope. The treatments resulted in five bare and four graveled road segments.

Rainfall simulation study--Six road approaches to three unimproved ford stream crossings on an abandoned legacy road at RHFRRC were bladed with a bulldozer in late July 2011 in a similar manner to that described above. Open-top box culverts (Trimble and Sartz 1957) were installed at the base of the stream crossing approaches to redirect stormwater runoff toward a 2.5- by 45.7-cm cutthroat flume (Tracom Fiberglass Products, Alpharetta, GA) where runoff volumes were measured during rainfall simulation experiments. Prior to the Bare treatment rainfall simulations, road approaches were tracked with a bulldozer to create conditions of 90 to 100 percent bare soil. Following the Bare treatment rainfall simulations, a dump truck was used to spread a mixture of size 3, 5, and 7 (5.1 to 1.9 cm in diameter) granite gravel at the base of the stream crossing approaches to the following standards: gravel depth = 7.6 cm; width = width of the running surface (mean = 3.0 m); and length = 9.8 m. This treatment was called Gravel 1, and it resulted in 25 to 50 percent gravel surface coverage on the approaches. Following the Gravel 1 rainfall simulations, an additional 9.8 m section of gravel was added to double the length of the first application. This treatment was called Gravel 2, and it resulted in 50 to 100 percent gravel surface coverage on the approaches. Gravel cost $27.78/Mg ($25 per ton) and applying the gravel to a depth of 7.6 cm for a running surface width of 3.0 m resulted in a cost per linear meter of $10.27.

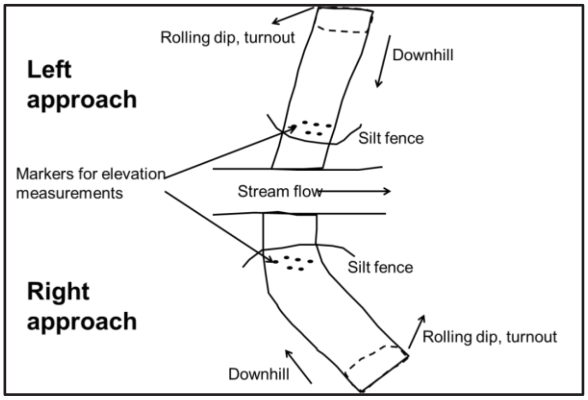

Figure 1--Plan view of the sediment trap study plots and instrumentation.

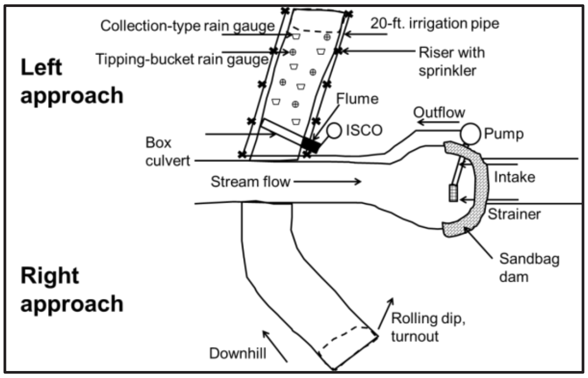

Figure 2--Plan view of the rainfall simulation study plots and instrumentation.

A high-pressure pump with an 18-horsepower gas-driven engine and a maximum flow rate of 37.9 L/second was used to pump source water for the rainfall simulation experiments from temporary impoundments that were created approximately 50 m downstream of each stream crossing (fig. 2). The irrigation setup included a 10.2-cm intake hose with a strainer, a 7.6-cm outflow component, and fire hose to connect to 7.6-cm aluminum irrigation pipelines that ran parallel to the road approach and on both sides of the road. A 3.0-m pipe and 90° angle couplings joined the two parallel segments of pipe at the base of the road plot. The pipelines ran on each side of the road surface and consisted of 6.1-m irrigation pipes that were coupled together for the length of the approach. A water control structure and open-top box culvert served as the upper and lower boundaries of the road approach plots, respectively. Similar to the silt fence study plots, in-sloping and outboard edge berm installation were used to redirect all runoff and sediment to the box culverts at the base of the plots. Quick coupling risers with sprinkler heads were located at 6.4-m intervals along the study plots, and they stood 3.4-m high. The same irrigation pipe and risers were used previously in rainfall simulation experiments to test agricultural BMP effectiveness to minimize soil erosion during rain events (Dillaha and others 1988). The irrigation setup is designed to apply rainfall to the study plots at a rate of 5.1 cm hour^{-1}. A series of three rainfall simulation experiments, ranging in length from 10 to 50 minutes, were performed for each treatment (Bare, Gravel 1, and Gravel 2) for each of the six road approach study plots for a total of 3 x 3 x 6 = 54 rainfall simulation experiments.

Field Measurements

Sediment trap study--A network of erosion pins and differential leveling with a total station was used to approximate monthly sediment deposition at the silt fences between August 2011 and August 2012. Sediment volumes (m^3) for each measurement interval were calculated by multiplying road surface depositional area (m^2) by elevation gain (m). Sediment volumes were converted to a sediment load (Mg) by multiplying by bulk density (Mg m^{-3}) of the trapped sediment. Bulk densities were obtained for the sediment sampled via the soil exaction method (SSSA 1986). Hourly rainfall data obtained from a Soil Climate Analysis Network weather station (NRCS 2010) located approximately 0.8 km from the study sites were summed to calculate total rainfall per measurement interval. Mean rainfall intensity (cm hour^{-1}) was also calculated for each measurement interval.

Rainfall simulation study--Rainfall amount and intensity were measured with six wedge collection-type rain gauges and five automatic tipping-bucket rain gauges (ECRN-50 Low-Resolution Rain Gauge, Decagon Devices, Inc., Pullman, WA) that were set to log data at 1-minute intervals. Surface runoff volume was measured with a 2.5- by 45.7-cm cutthroat flume fitted to the outflow end of the open-top box culverts. The flume was equipped with a pressure transducer (HOBO U20 Water Level Data Logger, Onset Computer Corporation, Bourne, MA) to measure water level at 1-minute intervals. Water level data was converted to discharge (L second^{-1}) through the use of a stage-discharge equation for the specific dimensions of the cutthroat flume. An ISCO automatic stormwater sampler (ISCO 3700 Series, Teledyne ISCO, Lincoln, NE) was programmed to collect 500 mL samples of stormwater runoff from the water flowing through the flume at 2- to 5-minute intervals, depending on the duration of the rainfall simulation event. Stormwater runoff samples were analyzed in the lab for total suspended solids (TSS, in g L^{-1}) by way of vacuum filtration of a known amount of sample volume and obtaining dry weights of the sediment trapped by the filters.

Statistical Analysis

Differences in median sediment delivery per measurement interval by road surface type (bare, graveled) were analyzed with a Wilcoxon signed-rank test (d.f. = 1; N = 117; $\alpha = 0.10$). Differences in median TSS concentration of surface runoff (g L^{-1}) by treatment type (Bare, Gravel 1, Gravel 2) were analyzed with a Kruskal-Wallis rank sum test (d.f. = 2 ; N = 681; $\alpha = 0.05$), and Steel-Dwass all pairs nonparametric comparisons were used to determine statistically significant groups.

RESULTS AND DISCUSSION

Field Measurements

Sediment trap study--Total rainfall during the study period (August 5, 2011 to August 5, 2012) was 1495 mm. Mean annual sediment delivery for the reopened bare approaches (98 Mg ha^{-1} year^{-1}) was 7.5 times greater than that of the gravel approaches (13 Mg ha^{-1} year^{-1}). Problem road approaches were associated with inadequate water control (> 75 m intervals for water control structures) and 90 to 100 percent bare soil conditions throughout the year. Reopened bare road approaches having both forest canopy cover during the growing season and litterfall ground coverage during the fall and winter months had lower sediment delivery rates than bare approaches located in a clearcut area with 4-year-old loblolly pine regeneration (fig. 3). Median sediment delivery per measurement period was 2.0 Mg ha^{-1} for the bare plots and 0.3 Mg ha^{-1} for the gravel plots (Chi-square statistic = 22.2, d.f. = 1, $p < 0.0001$). These findings exemplify the importance of proper implementation of water control and gravel surfacing BMPs to minimize direct inputs of surface runoff and sediment from forest road approaches to stream crossings. For haul roads, the Virginia Department of Forestry BMP manual recommends that gravel surfacing be used to cover the entire road approach that is delivering sediment to the stream and to redistribute stormwater runoff from the road surface and out over a well-vegetated or rough surface at least 7.6 m before the stream crossing (VDOF 2011).

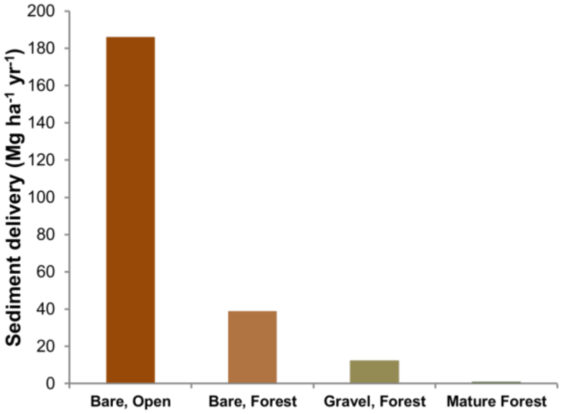

Figure 3--Mean sediment delivery rate (Mg ha^{-1} year^{-1}) by road surface type (bare, gravel) and forest canopy cover (open, forest) as compared with typical erosion rates in a mature forest setting. Canopy cover during the growing season and litterfall during the fall and winter seasons helped to reduce bare soil percentages, and thus sediment delivery rates at the “Bare, Forest” sites.

Rainfall simulation study--Simulated rainfall events had recurrence intervals of < 1 to 5 years for Critz, VA. Surface runoff was commonly generated within the first 5 minutes of the onset of rainfall. Gravel application reduced TSS concentration of surface runoff from the road approach study plots (fig. 4). Median TSS concentration of road surface runoff (g L^{-1}) for the Bare treatment rainfall simulations (2.34 g L^{-1}; 90 to 100 percent bare soil conditions) was 1.8 times greater than Gravel 1 (1.32 g L^{-1}; 25 to 50 percent gravel surface coverage) and 3.3 times greater than Gravel 2 (0.72 g L^{-1}; 50 to 100 percent gravel surface coverage). All treatments were significantly different (Bare > Gravel 1 > of

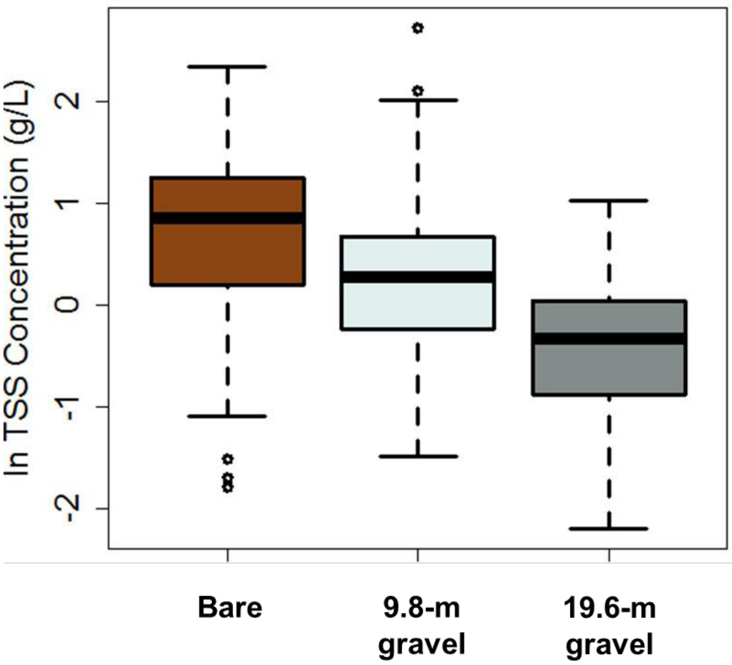

Figure 4--Box and whisker plots (showing the 5th, 25th, 50th, 75th, and 95th percentiles) of natural log-transformed TSS concentration of surface runoff (g L^{-1}) for all of the rainfall simulation experiments by treatment type (Bare, Gravel 1, and Gravel 2). N = 228, 222, and 231 for the Bare, Gravel 1, and Gravel 2 treatments, respectively.

Gravel 2). Local granite gravel cost for a mixture of size 3, 5, and 7 (5.1 to 1.9 cm diameter) was $27.56/Mg ($25 per ton). For a gravel application depth of 7.6 cm (3 inches), the cost surfacing the stream crossing approaches was$10.27/m ($3.13 per foot) of approach length.

CONCLUSIONS

Legacy roads and associated stream crossings have the potential to deliver significant quantities of sediment to streams if the roads have inadequate water control, are too steep, or lack surface cover. Therefore, upon reopening, legacy roads may require corrective BMPs to protect water quality. Corrective BMPs, such as gravel, can minimize the sediment contributions of stream crossing approaches. Judicious BMP implementation can reduce sediment inputs to streams and strike a balance between sediment reduction efficacy and BMP implementation cost. Many of the potential threats to water quality associated with forest roads, as well as the cost associated with corrective BMP implementation, can be minimized through pre-harvest planning to properly locate forest roads, minimize road length and stream crossings, and control grade, water, and erosion. Therefore, careful road design is an important BMP in itself.

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