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Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia Piedmont

Kristopher R. Brown [a,*], W. Michael Aust [b,1], Kevin J. McGuire [c,2]

[a] Department of Forest Resources and Environmental Conservation (FREC), Virginia Tech, 210 Cheatham Hall, 310 West Campus Drive, Blacksburg, VA 24061, United States
[b] FREC, Virginia Tech, 228D Cheatham Hall, 310 West Campus Drive, Blacksburg, VA 24061, United States
[c] FREC and Virginia Water Resources Research Center, Virginia Tech, 210 Cheatham Hall, 310 West Campus Drive, Blacksburg, VA 24061, United States

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ABSTRACT

Forest road stream crossing approaches, or the section of road immediately adjacent to the stream crossing, represent primary sources and nearly direct pathways for sediment delivery to stream channels. This research quantified sediment delivery rates associated with reopening abandoned legacy road stream crossing approaches and evaluated the effectiveness of gravel surfacing of the entire running surface in reducing sediment delivery at stream crossings in the Virginia Piedmont. Sediment delivery rates from five regraded (bare) legacy road approaches were compared to those from four completely graveled road approaches. Repeated measurements of road derived sediment trapped by silt fences were used to quantify sediment delivery rates from the road approaches for one year (Aug. 5, 2011–Aug. 5, 2012). Annual sediment delivery rates from the bare approaches were 7.5 times higher than those of the gravel approaches. Sediment delivery rates ranged from 34 to 287 Mg ha^{-1} year^{-1} for the bare approaches and from 10 to 16 Mg ha^{-1} year^{-1} for the graveled approaches. The highest sediment delivery rates were associated inadequate road surface cover and insufficient water control structures. These findings show that reopened legacy roads and associated stream crossing approaches can deliver significant quantities of sediment if roads are not adequately closed or maintained and that corrective best management practices (BMPs), such as gravel and appropriate spacing of water control structures, can reduce sediment delivery to streams.

1. Introduction

Soil erosion and subsequent sediment delivery to streams associated with low-standard roads is consistently cited as a primary source of pollution within forested land use (Anderson and Lockaby, 2011; Croke and Hairsine, 2006; Grace, 2005a,b; Luce, 2002). Roads are an essential component for many forest management activities and provide access for timber harvest operations, site preparation activities, fire management, insect and disease control, and recreational opportunities. Road surfaces are compact and largely impervious by design to provide access for pre-planned traffic volumes, vehicle types, and loads, which are a function of land use objectives and tract area to be served by the road. Compact surfaces, including permanent and temporary roads, skid trails, and log decks, represent the primary instances in forested environments where infiltration-excess overland flow is possible even for low-intensity rain events (Ziegler et al., 2007). Subsurface hillslope flow interception from insloped or through-cut roads with cutslopes and ditches can dominate road surface runoff during rain events because the drainage area of the hillslope is often greater than that of the road surface (MacDonald et al., 2001; Wemple and Jones, 2003). This condition of enhanced infiltration-excess overland flow can increase road surface erosion.

Poorly designed or maintained forest road networks can increase hydrologic connectivity (drainage density) to streams by routing stormwater runoff through roadside ditches that connect directly to streams at road stream crossings, as well as further away from stream channels when gullies form below surface runoff relief culverts (Wemple et al., 1996). This increased hydrologic connectivity may impact the timing and magnitude of streamflow response to rain events and increase the frequency and magnitude of flood flows (Beschta et al., 2000; Eisenbies et al., 2007; La Marche and Lettenmaier, 2001). These direct hydrologic connections can adversely impact water quality through increased sedimentation from road erosion sources, while increased stormwater runoff may induce stream geomorphological changes, re-mobilize existing sediment stored within the stream channel, and result in the degradation of aquatic habitat (Goode et al., 2012).

* Corresponding author. Tel.: +1 (563) 260 3431.
E-mail addresses: krisrb3@vt.edu (K.R. Brown), waust@vt.edu (W. Michael Aust), kevin.mcguire@vt.edu (K.J. McGuire).
[1] Tel.: +1 (540) 231 4523.
[2] Tel.: +1 (540) 231 6017.

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Chronic fine sediment contributions associated with hydrologic connectivity between road networks and stream channels pose issues for water quality and aquatic habitat degradation (Goode et al., 2012; Robinson et al., 2010), which was underscored by the 2012 US Supreme Court consideration of the Ninth Circuit Court ruling that was initiated by *Northwest Environmental Defense Center v. 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 US (Boston, 2012). The US Supreme Court decision retained the nonpoint source pollution (NPSP) status of forest roads and silvicultural exemptions by reversing the Ninth Circuit ruling in March of 2013, but further litigation is possible until the NPSP status of forest roads is clarified. Nevertheless, it is clear that improved cost-effectiveness and implementation of forest road BMPs are critical for water quality protection.

Reduced-impact forestry utilizes BMPs to minimize the impacts of forest roads on water quality. BMPs for road design include adequate consideration of appropriate road standards and planning the layout of road networks to minimize stream crossings and control road gradient (Walbridge, 1997). Water control structures, such as ditches with relief culverts, broad based dips, water bars, and turnouts, are used to drain insloped road surfaces and minimize the travel length of overland flow (Keller and Sherar, 2003). Vehicles with low-pressure tires may be implemented to minimize the impacts of traffic on road surface erosion (Foltz and Elliot, 1997). Road surfacing techniques, such as the use of gravel, are used to enhance trafficability and minimize soil erosion on active roads (Clinton and Vose, 2003; Kochenderfer and Helvey, 1987; Swift, 1984). During road closure, techniques to control erosion and sediment delivery include traffic restriction and natural vegetation reestablishment for temporary closure. Road decommissioning may also include soil ripping to alleviate compaction, recontouring and culvert removal to restore natural drainage patterns, replanting with native vegetation, and stream crossing removal and stabilization for permanent abandonment.

Research has shown that properly implemented BMPs reduce soil erosion and protect water quality (Anderson and Lockaby, 2011; Aust and Blinn, 2004; Stuart and Edwards, 2006). However, most BMP effectiveness studies have focused on quantifying soil erosion and not sediment delivery to stream channels from specific forest management operations (i.e., timber harvesting, site preparation, roads, skid trails, log decks) (Croke and Hairsine, 2006; Grace, 2005a,b). The difficulty in quantifying sediment delivery ratios is that only a portion of upslope soil erosion reaches the stream due to factors such as the distance between the road and the stream, as well as watershed topographic characteristics (e.g., breaks in grade or depressions) and surface roughness features that act to trap and store sediment transported by surface runoff.

Research that has focused on quantifying sediment delivery potential from forest roads suggests that the degree of hydrologic connectivity of a road can be highly variable and site specific (i.e., dependent on catchment characteristics such as slope, road location, spacing of water control structures, and road and drainage density) (Takken et al., 2008). Sun and McNulty (1998) developed a sediment routing system by coupling a Geographical Information System (GIS) and the Universal Soil Loss Equation modified for forest land (USLE-forest) (Dissmeyer and Foster, 1984) and calculated sediment delivery ratios for well-managed (0.15:1) and poorly managed (0.36:1) logging roads in the Blue Ridge Mountains of southwestern North Carolina. Previous studies in the Piedmont region of the US have estimated sediment delivery ratios associated with harvesting, prescribed burning, and replanting (Lakel et al., 2010) and harvesting, mechanical and chemical site preparation, and planting (Ward and Jackson, 2004). In both studies, upslope erosion rates were modeled with either the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) or USLE-forest (Dissmeyer and Foster, 1984) and compared with field measurements of trapped sediment at or within streamside management zone (SMZ) boundaries. Lakel et al. (2010) estimated sediment delivery ratios for forest operations (including roads and skid trails) to be between 0.03:1 and 0.14:1, while Ward and Jackson (2004) estimated a sediment delivery ratio of 0.25:1 for areas having mechanical site preparation. Both studies recognized the importance of adequate SMZs for trapping sediment before it entered streams and Lakel et al. (2010) emphasized that stream crossings were a major mechanism for increasing sedimentation by penetrating the SMZ.

Few BMP effectiveness studies have measured both soil erosion and sediment delivery rates associated with specific locations and management activities within forest operational areas. However, it is well established that BMP failures (i.e., problem areas for sediment delivery) are often non-uniformly distributed, represent small proportions of the total forest operational area, and contribute disproportionate amounts of sediment to the stream (Rivenbark and Jackson, 2004). Most often, these areas are associated with inadequate BMP implementation for forest roads and trails. These sediment delivery hotspots often exhibit one or more of the following characteristics: large contributing areas (mean = 0.4 ha (Rivenbark and Jackson, 2004)), areas of convergence (e.g., gullies and swales), compacted soils, minimal surface cover and roughness, and steep slopes (Lakel et al., 2010; Litschert and MacDonald, 2009; Rivenbark and Jackson, 2004; Swift, 1986).

Progress toward the prediction of high-risk areas for water quality degradation in light of current and future forest management operations include the development and field testing of soil erosion and hydrologic models and sediment tracing methods (Anderson and Lockaby, 2011; Fu et al., 2010). Concurrent field studies should focus on minimizing erosion where sediment has the highest probability of being delivered to the stream, while gaining valuable field data with which to test model performance. Hydrologic and soil erosion models have been developed to assist land managers in identifying high-risk areas for sediment delivery and implementing appropriate BMPs for water quality protection. Several state and federal organizations, including the Virginia Department of Forestry (VDOF), the State Foresters Council for the Southeast US, and the United States Department of Agriculture (USDA) Forest Service are interested in implementing the Water Erosion Prediction Project (WEPP) model to predict forest road soil erosion and sediment delivery. WEPP is a physics-based soil erosion and hydrologic model developed by the USDA Natural Resource Conservation Service and Forest Service that estimates soil loss and sediment yields from hillslope erosion at the small catchment scale (Flanagan and Nearing, 1995). WEPP is capable of partitioning road erosion and sediment delivery into individual road features, such as the road surface, cutslope, fillslope, ditch, and lower hillslope (Fu et al., 2010). Previous studies have shown that WEPP is potentially useful for estimating soil erosion from forest roads, where overland flow is the dominant runoff process (Dun et al., 2009; Elliot et al., 1999; Grace, 2005a,b; Laflen et al., 2004). Empirical models, such as the Universal Soil Loss Equation adapted for forest land (USLE-forest) (Dissmeyer and Foster, 1984) and RUSLE2 (Foster et al., 2003) have been used comparatively with WEPP to predict erosion associated with various road closure BMPs for bladed and overland skid trails in the Virginia Piedmont (Sawyers et al., 2012; Wade et al., 2012a,b). However, model performance has not been evaluated at the road-stream interface for a wide range of approach characteristics, BMP implementation, and rainfall conditions. Such approaches are critically important because the US EPA is currently requesting that state forestry organizations further quantify the relationship between