Efficacy of Operational Stream Crossing Best Management Practices on Truck Roads and Skid Trails in the Mountains, Piedmont, and Coastal Plain of Virginia

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ABSTRACT (ACADEMIC)

Forestry best management practices (BMPs) programs were developed by individual states in response to the Clean Water Act in order to protect water quality during and after timber harvests. Our research goals are to compare BMP implementation at stream crossings by region and road type in Virginia and to quantify effectiveness of BMPs by developing hypothetical upgrades and determining upgrade costs. Stream crossings (75 truck, 79 skidder) sampled for BMP implementation were on operational harvests conducted in 2016, from the Mountains, Piedmont, and Coastal Plain of Virginia. Erosion rates of stream crossing approaches were modeled using the Universal Soil Loss Equation modified for forest lands (USLE-Forest) and Water Erosion Prediction Project (WEPP) methodologies. Implementation ratings (BMP-, BMP-standard, BMP+) were developed to characterize crossings with respect to state implementation standards. Costs for upgrading crossings to a higher BMP category were estimated by adjusting cover percentages and approach lengths. Sixty-three percent of stream crossings were classified as BMP-standard, with an average erosion rate of 7.6 Mg/ha/yr; 25% of crossings were classified as BMP+, with an average erosion rate of 1.7 Mg/ha/yr; and 12% of crossings were classified as BMP-, with an average erosion rate of 26.2 Mg/ha/yr. Potential erosion rates decreased with increasing BMP implementation ($p < 0.0001$). Average BMP implementation audit scores for stream crossings were 88% on skid trails and 82% on truck roads. To upgrade from a BMP- to BMP-standard, the cost-benefit ratio of dollars to tons of sediment prevented averaged $166.62/Mg for skid trails and $2274.22/Mg for truck roads. Enhancement to the BMP+ level

not economically efficient and BMP implementation at stream crossings reaches maximum efficiency at the BMP-standard level.

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ABSTRACT (GENERAL AUDIENCE)

Timber harvesting can accelerate erosion processes and result in the discharge of large quantities of sediment into nearby water resources if proper management is not used during and after harvests. Most of sediment entering streams is generated from forest roads and trails, particularly at stream crossings. This study includes 154 crossings (75 truck, 78 skidder) randomly selected from the Mountains, Piedmont, and Coastal Plain regions of Virginia. Evaluations were conducted on lands with silvicultural operations completed in 2016 that had truck road crossings and/or skidder crossings over any stream. Information was gathered at each crossing to model the erosion rates from both approaches to the stream by using the Universal Soil Loss Equation modified for forest lands and the Water Erosion Prediction Project. Implementation ratings (BMP-, BMP-standard, BMP+) were developed to characterize crossings with respect to state implementation standards, and evaluate other factors, including stream bank stability, ground cover, and evidence of sedimentation in the stream. The Virginia Department of Forestry BMP audit was used to score the crossings. Costs for upgrading the crossing to a higher BMP category were estimated by adjusting cover and approach lengths, and then using previous research data and existing road cost models. Potential erosion rates decreased with increasing BMP implementation ($p < 0.0001$). Average BMP implementation audit scores for stream crossings were 88% on skid trails and 82% on truck roads. This research contributes to the evidence of BMP effectiveness and provides transparency to the citizens of Virginia regarding sustainable forestry practices.

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1.0 INTRODUCTION

1.1 Background and Policy

The Federal Water Pollution Control Act (FWPCA) of 1948 was approved to address water pollution in the United States. Amended in 1972, it became known as the Clean Water Act (CWA). The CWA protects water quality of U.S. navigable waterways and their tributaries by regulating point source pollution (PSP) through the National Pollutant Discharge Elimination System (NPDES), and nonpoint source pollution (NPSP) through state initiatives. Following passage of the CWA, forestry best management practices (BMPs) were developed as state programs to minimize the potential impacts to water quality from forest operations. Although BMPs are designed to protect against several types of NPSP (chemical, nutrient, organic, thermal, and sediment), federal and state forestry agencies particularly advocate BMPs as a method of erosion control that will protect the waters of the United States by reducing sedimentation (Zhuang et al. 2016). Emphasis is often placed on sedimentation because sediment is the most common water pollutant following timber harvests in the US (Anderson and Lockaby 2011a). Sediment discharges that are potentially harmful to streams are most often associated with roads, skid trails, and stream crossings because these installations cause disturbances to forest litter and cover and road networks may create direct linkages to streams (Swift and Burns 1999). Previous research regarding fluvial geomorphology and forestry agree that "the most important control of soil loss from commercial forests is the extent and nature of road construction" (Dunne and Leopold 1978). Harvesting operations, excluding roads and skid trails, create minimum and short-term effects on water quality when BMPs are in place (Aust and Blinn 2004).

Forestry is a major land use across the southeastern United States, which has become the largest wood producing region in the U.S. (Bentley and Cooper 2015). Numerous studies have shown that forest management is a relatively benign and sustainable land use when appropriate and adequate BMPs are used (Anderson and Lockaby 2011b; Aust and Blinn 2004; Ice et al. 2010; Shepard 2006). Although silvicultural operations typically produce low levels of sediment relative to other anthropogenic uses, such as agriculture, urban development, and mining (Cristan et al. 2016), some specific forest operations associated with access (roads, skid trails, stream crossings) have the potential to cause adverse sedimentation if erosion control measures are not carefully implemented (Aust et al. 2011; Brown et al. 2015). Stream crossings are of particular concern because these are sediment entry points for both roads and skid trails that can act as overland flow paths (Pechenick et al. 2014) and effectively increase stream density (Croke and Mockler 2001). Stream crossings also bisect stream side management zones (SMZs) and compromise the protective sediment buffer (Lakel et al. 2010; Lang et al. 2015). Focus on stream crossings was recently elevated by the recent case (NEDC v. Brown/Decker) that went through several levels of federal courts before reaching the US Supreme Court (Boston 2012). In 2011, the Ninth Circuit appellate court ruled that stormwater runoff from logging roads passing through man-made culverts in the state of Oregon was a form of point source pollution and required a USEPA permit to discharge the water into local streams and rivers (Whitlock et al. 2013). Logging roads are excluded from the NPDES under the Silviculture Rule in the Clean Water Act. The NPDES exempts activities including reforestation, thinning, road construction, and harvesting operations, deeming their byproducts a form of non-point source pollution. The Supreme Court reversed the Ninth Circuit appeal in 2013, ratifying the Silviculture Rule. This case, which focused on forest stream crossings and sediment, emphasized the need and utility of documentation, evaluation, and quantification of BMP effects at forest stream crossings.

While BMPs in many states are voluntary, the Clean Water Act is a mandatory law that facilitated by voluntary BMPs (Sawyers et al. 2012; Cristan et al. 2018). BMP recommendations vary by state, but state BMP programs generally advocate minimization of bare soil and soil compaction; separation of erosive conditions from surface waters; careful and controlled application of fertilizers and pesticides; inhibition of breakthroughs to nearby streams; provision of a forested buffer around streams; design and construction of stable forest roads and stream crossings; and minimize harvesting on steep terrain (Jackson and Kolka 2002). BMPs are site specific, and the BMP state manuals are adjusted accordingly as research continues to prove significant linkages between site productivity and management of natural resources. The forest industry has set precedent for future operations through organizations and policies like the Sustainable Forestry Initiative (SFI) and the Forest Stewardship Council (FSC). The success and continuation of forest operations depends on the implementation of best management practices by loggers as they harvest timber and as they close out a tract.

1.2 Land Characteristics of Virginia

The commonwealth of Virginia can be described by regional climates, drainage, parent materials, soils, and topography, and is divided into five physiographic provinces that reflect such characteristics. Average precipitation in Virginia is 43 inches per year, which doesn’t vary much with ecoregion. Rainfall runoff does vary slightly by region, but remains within the range of 125-250 EI units.

The coastal plain of Virginia is the eastern portion of the state and is defined by uncemented river and marine sediments. This ecoregion consists of some well-drained sandy soils, as well as wet pine flats, forested wetlands, and poorly drained soils as the state progresses eastward to the Atlantic coast. Land cover primarily consists of agricultural fields, pine plantations, natural pine and hardwoods, and urban civilization.

The piedmont region has undergone severe erosion due to intensive farming practices followed by several waves of agricultural abandonment. Current land use includes pasture lands with some woodlands; natural pine and hardwoods stands, and pine plantations. Parent materials include igneous and metamorphic rock, which have weathered to produce soils with high clay percentages, but depleted and leached nutrients, leaving an acidic, low productivity soil. Mica is commonly present in the piedmont saprolite.

Virginia has three physiographic regions that are considered mountainous. The Blue Ridge of Virginia has igneous and metamorphic bedrock, but less weathered soils, and more abundant rock fragments and limiting layer of fragipan. Gneiss and granite are common rocks found in the region. The Ridge and Valley province has sedimentary rock parent material that is commonly folded shale and sandstone, and cleared valleys with limestone bedrock. This area is more eroded than the neighboring Appalachian Plateau, which consists of long steep slopes, but leveled ridgetops and downcutting streams. This area is also abundant in shale and sandstone, with early river terraces that border the active floodplains.

1.3 Logging Characteristics in Virginia

The forest industry in Virginia is the third largest economic industry, providing over $17 billion to the state’s economy each year and employing 103,000 citizens (VDOF 2016). Forest harvesting operations may reflect localized or regional characteristics. Forest harvesting is limited by terrain, soil productivity and conditions, climate, wood markets, and socioeconomic factors that are particular to each of Virginia’s regions. Based on a 2014 logging survey, 88.4% of loggers in the mountainous region of Virginia commonly use a chainsaw as their primary mechanism for felling, and 48% use cable skidding as their form of primary transport (Barrett et al. 2017). Weekly production and crew size are commonly lower in the mountains as steep terrain limits the harvesting mechanisms allowable. In the piedmont and coastal plain regions, rubber-tired feller-bunchers and grapple skidders are most common. These highly mechanized systems accommodate larger logging crews and high volumes of production. Harvest type and product can vary substantially by region. Hardwood sawtimber harvested in a clearcut and select cuts are most common in the mountains, while pine sawtimber and pulpwood are most frequently harvested in clearcuts and thinnings in the coastal plain and piedmont.

1.4 Literature Review

1.4.1 Erosion and BMPs for Skid Trails

In response to the passage of the CWA in 1972, several studies were conducted in the southeast to investigate the effect of forest operations on streams. These studies include the works of J. D. Hewlett (1979), who used H flumes to model the hillslope hydrology and erosion after silvicultural practices in the Georgia Piedmont. Hewlett used two neighboring watersheds, similar in soils, topography, climate, and hydrology, consisting of first order headwater streams to compare a clearcut harvest and replanting with a no-harvest control. The treatment area was harvested utilizing rubber tired skidders and replanted by machine on contour. They left a thinned six-meter buffer along the stream. Hewlett's results showed 5X the hillslope erosion after harvest and 26X erosion after planting, which yielded about 92 kg/ha/yr. Erosion rates increased and remained elevated for the first two years in the treatment area, but the watershed recovered to pre-harvest levels by year six. There were several ephemeral crossings where the loggers used brush matting to cross, and they determined that this area contributed more sediment than the areas where silvicultural activities occurred. Jackson revisited the watersheds

30 years later to conduct the same experiment using upgraded BMPs pertaining to the 1999 Georgia recommendations. They found that using 12-21 meter buffers (dependent upon slope) and better road drainage was sufficient to maintain base levels of erosion to the stream. Stream temperature and sedimentation was not significantly affected in the treatment watershed. The study concluded that modern silvicultural BMPs that include wider SMZs and fewer crossings are likely to reduce forestry effects on water quality (Fraser et al. 2012). The study also found that bank stability is crucial in reducing sediment delivery to the stream. Local bank slumps can deposit 1000 kg of sediment within seconds if a crossing is installed or removed incorrectly; this can be especially true in regions like the Piedmont and Mountains, where steep slopes, unstable bed material, and incised channels are fairly common.

Soil erosion from skid trails can reduce water and habitat quality, create a path of channelized erosion, and remove the topsoil, which alters soil properties, ultimately decreasing site productivity. Wade et al. (2012) determined the effectiveness of different levels of BMP prescriptions on six bladed skid trails at the Virginia Tech Reynolds Homestead Forest Resources Research Center in Patrick County, VA. The five treatments included: (1) water bar only, (2) water bar with seed, (3) water bar with seed and mulch, (4) water bar with hardwood slash, and (5) water bar with pine slash. Treatments were applied randomly to six blocks on each trail, and erosion was collected using geotextile traps. The grass seed and mulch combination proved the most effective at trapping sediment, although there was no statistically significant difference between the mulch and slash treatments. This study concluded that the bare minimum BMP (water bar) may not be sufficient on approaches that are steep or have naturally high erosion rates, and that ground cover is essential for reducing erosion following a harvest, especially during wetter periods of the year. Sawyers et al. (2012) assessed skid trail closure costs and effectiveness by using the same five treatments as Wade et al. (2012) on overland skid trails at the Reynolds Homestead. They measured sediment loss, finding again, that the mulch treatment was the most effective at reducing erosion, with hardwood slash as the next best option. Wear et al. (2013) conducted a study at five harvest sites in the Virginia Piedmont, using similar treatments on stream crossing approaches: slash only, grass seed/mulch, grass seed/mulch/silt fence. Both slash and grass seed/mulch treatments effectively reduced total suspended solids. In addition, they found that the silt fence treatment worsened the site conditions and increased the suspended solids concentration due to soil disturbance from installation. These studies are in agreement that slash is the all-around best option to close out a skid trail. It takes the longest time to decompose, providing more cover for a longer amount of time, especially as grass can be difficult to establish depending on site conditions and season. It prevents unwanted travel (e.g. ATVs) and is usually the cheapest and easiest option for loggers as they complete operations.

1.4.2 Erosion and BMPs for Truck Roads

Roads can produce unfavorable impacts to the environment, including modified natural drainage patterns, increased erosion, altered natural terrain, and land area disturbance. Brown et al. (2013) conducted research in Patrick County, VA, to determine the effect of cover on sedimentation rates by reopening legacy roads that approached streams. The results indicated that completely graveled approaches yielded 7.5X less sediment than bare approaches. Improper crossing structures and/or insufficient ground cover caused the highest rates of sedimentation. They also found that poorly designed or maintained road networks can increase hydrologic connectivity (gullies and ditches), causing frequency and magnitude of flood flows to potentially increase. With increased connectivity, modified landscapes have the ability to disrupt the sediment regime, causing streams to aggrade over time due to a sediment supply that exceeds the transport capacity of that channel (Jackson and Pringle 2010). A change in timing and magnitude of rainfall events will produce more stormwater runoff, which can lead to fluvial geomorphic changes and degradation to aquatic habitat (Brown et al. 2013). A follow up study was conducted in 2015 using rainfall simulation experiments on a series of gravel-treated approaches of reopened roads. Hydraulic conductivity increased with increasing particle size of the gravel, allowing for greater infiltration to occur (Brown et al. 2015). Rain gauges were used to measure intensity and volume, and ISCOs were used to collect sediment samples (TSS). The study concluded that gravel application reduced TSS concentrations of road surface runoff.

Morris et al. (2016) completed a study at the same crossings studied by Brown et al. (2013) measuring the effectiveness of three levels of BMP treatments on three crossing structures (bridge, ford, and culvert). Rainfall simulations were used at differing levels of intensity to represent erosion in varying climate conditions. Total suspended solid concentrations were sampled upstream and downstream of the crossing during crossing construction and after the rainfall simulations. Two of the three crossings showed decreased sediment load with increased BMP level. The bridge produced the least stream sediment during construction, but it was the most expensive treatment considered. However, the cost per use of a bridge is reduced when portable temporary bridges are used. The lowest level of BMP bridge treatment (BMP-) was still a better BMP option than the higher BMP level culvert and ford stream crossings tested for minimizing in-stream sediment concentrations.

Aust et al. (2011) examined 23 stream crossings, assessing water quality indices upstream, downstream, and from each approach consisting of a culvert, ford, pole bridge, or portable bridge. These sites were examined four times during operational harvests. Water quality parameters were most negatively affected during the installation and harvest periods and improved during closure. Bridges proved to be the least disruptive crossing type, and had even better results when the bridges were only temporary rather than permanent, most likely due to a preserved streamside management zone (SMZ) that provided shade to the stream. SMZs can trap 70-99% of sediment from breakthroughs, stabilize stream banks, filter overland flow, and provide habitat complexity from downed woody debris, making SMZs an essential BMP to maintain water quality (Jackson and Kolka 2002). Culverts and fords were primarily used for permanent truck roads because these structures had more load bearing potential and the streams had bigger watersheds. Bridges were found most suitable for skid trails. The average sediment concentrations were greater downstream than the upstream counterparts. The highest estimate came from culverts during the harvest period, indicating that BMP implementation can have significant impact on the amount of sediment entering the stream. The Water Erosion Prediction Project (WEPP) and the Universal Soil Loss Equation modified for forestland (USLE-Forest) (Dissmeyer and Foster 1984) were used to estimate erosion rates from each crossing. The USLE-Forest erosion estimates have been compared to direct measures of erosion on several road and trail studies (e.g. Brown et al.2013; Sawyers et al. 2012; Vinson et al. 2017; Wade et al. 2012) and the values have been found to reflect erosion trends between BMP treatments even though actual quantities may vary. Lang et al. (2017) conducted a study in the Mountains and Piedmont and found that empirical models could predict erosion within five Mg if rates were less than 11.2 Mg/ha/yr.

Arthur et al. (1998) conducted a watershed study in eastern Kentucky, monitoring two harvested watersheds, one treated with BMPs, the other non-treated, which represented loggers unaware of water quality issues, and an uncut control watershed. BMPs included 50-foot buffer strips on each side of the stream, all road grades <10%, water control structures in place (e.g., broad-based dips, water bars), and seed planted after harvest. In the untreated watershed, logs were felled into the stream, no revegetation efforts were made, and no buffers were maintained. Prior to the harvests, there were no significant differences between the watersheds in sediment yield. The harvested watersheds produced significantly more sediment than the uncut watershed during and several months following harvest. Water yield increased significantly in both watersheds compared to the unharvested control. Both harvested sites exhibited higher sediment flux and nutrient concentrations; the watershed without BMP implementation displayed the highest fluxes. Five years after harvesting, the BMP-treated watershed showed no significant differences to the control, while the non-BMP treated watershed was still recovering, most likely due to the lack of roadside revegetation and drainage.

Rivenbark and Jackson (2004) performed a study on 30 harvest sites to identify areas where flow and/or sediment entered a streamside management zone and made its way to the stream, termed a "breakthrough," and areas where flow and sediment did not reach a stream, termed a "success." Breakthroughs were most often located where there was minimal litter cover, steep slopes, and a large contributing area. These factors are considered an essential part of the USLE-Forest equation used to estimate soil erosion in tons per acre per year. Unfortunately, there was no identifiable threshold to quantify the value of ground cover or limit the slope gradient to develop a concrete management ruling, most likely because of the individual situations of each site. Rivenbark and Jackson concluded that more strategically planned BMPs that are site specific might significantly reduce the amount of sediment entering a stream during and after forest operations in the Piedmont. Data revealed that 25% of the breakthroughs found in the study originated from forest roads and/or skid trails. The authors recommend the use of digital elevation models to accurately estimate the variable source areas that contribute sediment during the preharvest planning stages. They also advocate special attention to the agricultural gullies that plague the southeastern Piedmont by applying ample amounts of slash, which would ultimately improve BMP efficiency. Similar subsequent studies include Lang et al. (2015) and Brown and Visser (in press), which both identify breakthroughs on harvest sites to primarily exist at stream crossings.

1.4.3 Costs

Costs associated with BMPs have been difficult to quantify due to the fluctuating local economies, individual site conditions, and varying amounts of disturbance during operations. Several studies have developed methods and average estimations for BMP implementation by studying literature, conducting logger surveys, and performing onsite evaluations. Most relevant studies in the southeast have suggested that BMP costs can range from 1% to 5% of harvest sale revenues. In 1998, Shaffer et al. produced BMP costs per acre for the three regions of Virginia, which ranged from \$3.17/acre in the Coastal Plain to \$94.41/acre in the Mountains. The study determined that the variation was based on site conditions in the Mountains such as steep slopes, limited accessibility, and multiple small ephemeral streams. They also determined the median value of BMP costs in Virginia to be \$8.11/acre in the Coastal Plain, \$25.75/acre in the Piedmont, and \$29.29/acre in the Mountains. While the numbers have undeniably changed over the past two decades, the same increase in costs moving westward across the state is expected. Similar diminishing returns in the cost effectiveness estimates as seen by Aust et al. (1996) is also expected. While the benefits of increasing BMP implementation increased relatively rapidly, the costs increased moderately until about the 92% implementation level; the benefits reached a maximum and stabilized, while the costs escalated (Cubbage 2004).

McKee et al. (2012) performed a telephone survey including 70 loggers to inquire about the number, types, and costs of crossings and BMPs the contractors most commonly used. Costs for closures were typically highest in the Mountains, most likely due to reasons described by Shaffer et al. (1998), such as steep terrain, abundant headwater streams, and limited accessibility. Skidder crossings were more prevalent than truck road crossings, and portable bridges were favored in the Coastal Plain and Piedmont, although they were the most expensive option. Steel or wooden portable skidder bridges are very valuable to loggers despite their cost due to their easy installation and practicality (Aust et al. 2003). Loggers working in the Mountains chose culverts more readily than other structures, most likely because of the abundance of ephemeral and intermittent crossings. Loggers can avoid many costs and labor hours by carefully preparing routes to access the timber so that they encounter a minimum amount of stream crossings, which should be determined during preharvest planning (VDOF 2011).

The Virginia Tech Forest Road Cost Method (VTFRCM) (Conrad et al. 2012) is another estimation method used to determine the cost for building roads, stream crossings, and skid trails, as well as improving these structures and closing after harvest. It has the most practical use in the field when visiting a harvest site and desiring a rough, minimum estimate to meet the standard BMP requirements. Local companies, experienced professors, and other published information provided estimates for many of the costs required to comply with the standard forestry BMPs in Virginia. The multiple case studies used to test the VTFRCM for accuracy had results that came within 10% of the actual cost.

Overall, the literature clearly indicates that stream crossings have the potential to be major sources of sediment entry if appropriate BMPs are not used. The literature also indicates that additional BMP use at stream crossings may be restricted by increased cost. Thus, this project was designed to evaluate the efficacy of BMPs used at operational stream crossings while also evaluating the cost for enhanced levels of BMPs.

1.5 Research Objectives

A pilot study (Nolan et al. 2015) proved the basic concept of such a project by examining 20 truck road crossings and 22 skid trail crossings in the Piedmont of Virginia. They developed a BMP-, BMP-standard, and BMP+ rating system to characterize the crossings, and also estimated the potential erosion and costs that would result from enhanced BMPs at each crossing. We expanded the original pilot study to collect more data across additional regions of Virginia. This study characterized BMP effectiveness across the state by sampling 150 operational stream crossings (3 regions (Mountains, Piedmont, Coastal Plain) x 2 types of crossings (Truck, Skid) x 25 stream crossings). By looking at harvests completed within the past approximate six months, we quantified the effectiveness of current erosion control methods and how sites recovered over time. Two main objectives of the study were to 1) summarize the importance of the relationship between forest operations and water quality, and 2) quantify the effectiveness of stream crossing BMPs by using erosion and cost models. Chapter two summarizes the data and implications of skid trail crossing BMPs, erosion rates, costs for upgrades, and benefits associated with those enhancements. Chapter three addresses the same topics regarding truck roads. Chapter four consists of comparisons and contrasts between truck roads and skid trails, along with a synthesis of past studies and the VDOF BMP manual.

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2.0 THE EFFECTIVENESS OF FORESTRY BEST MANAGEMENT PRACTICES AT SKIDDER STREAM CROSSINGS IN VIRGINIA

2.1 Abstract

Sediment is the most common nonpoint source pollutant associated with timber harvesting in the southeastern U.S. Sediment is of particular concern at operational stream crossings because sediment delivery potential is heightened due to stream and trail proximity and the compromised streamside management zone. This study was developed to quantify the effectiveness of best management practices (BMPs) implemented at operational skidder stream crossings in three physiographic regions of Virginia. We assessed seventy-nine skid trail crossings based on implementation of state BMP manual recommendations, the Virginia Department of Forestry BMP audit, and potential soil erosion as predicted by Universal Soil Loss Equation-Forest methodology and Water Erosion Prediction Project: Road interface. Estimated erosion rates decreased with increasing BMP audit scores for skid trails ($p < 0.001$). BMP Ratings of substandard implementation (BMP-), implementation that met recommended guidelines (BMP-standard), or implementation that exceeded BMP guidelines (BMP+) were determined for each crossing. Hypothetical BMP upgrades were developed for crossings that did not meet the recommendations of the Virginia BMP manual and for those that reached a standard level, so that all crossings were hypothetically elevated to the BMP+ level. BMP-standard or BMP+ categorized crossings made up 92% of all skid trail stream crossings sampled, with average modelled potential erosion rates of ≤ 5.2 megagrams/hectare/year (2.3 tons/acre/year). Results verify that BMPs are effective for minimizing erosion at skidder stream crossings in Virginia. On average, costs for additional BMP implementation are efficient up to the BMP-standard level but outweigh the benefit substantially when upgraded to a BMP+.

Key words: best management practices—skid trails—stream crossings—erosion

Forestry Best Management Practices (BMPs) were generally formalized in the 1970's in direct response to the Federal Water Pollution Control Act of 1972 and its subsequent amendments (Cristan et al. 2018). The fundamental goal of BMPs is to protect water quality by minimizing disturbance, reducing erosive runoff on bare surfaces, and maintenance of soil properties that favor infiltration (Neary et al. 2010). For example, pre-harvest planning allows land managers to identify and protect streams and waterbodies with streamside management zones. During the pre-harvest planning phase appropriate locations for roads, skid trails, decks and stream crossings should be identified. Such preharvest activities allow the subsequent road construction and harvest operations to be conducted with minimal soil erosion and sedimentation (Kochenderfer 1970; Swift and Burns 1999). As roads and skid trails are constructed, water control and soil protection BMPs are implemented. Water control structures and soil cover options are effective erosion control methods that are immediate, cost effective, and feasible for loggers. Appropriately implemented BMPs such as these have been shown to reduce stream sediment concentrations by 52-94% (Edwards and Williard 2010).

2.2 Introduction

2.2.1 Background

The Federal Water Pollution Control Act of 1948, established as a general effort to improve water quality, was amended in 1972 to include the regulation of point source pollution into navigable waters. Specific goals were to regulate and reduce direct sources of discharge of contaminants into waterways that were used for transportation and drinking water supply through the National Pollutant Discharge Elimination System (NPDES) (Boston 2012). Implementation of the Clean Water Act and amendment clauses has substantially reduced point source pollutants, which are rarely an issue of intentional discharge and almost solely an issue of failed infrastructure.

The FWPCA of 1972 also addresses nonpoint source pollutants, which do not have easily identifiable sources, yet can have negative water quality consequences. Biological nutrients (phosphorus, nitrogen, toxins, and heavy metals), chemical nutrients (pesticides and herbicides), and sediment have the potential to be erosion transported pollutants. Nonpoint source pollutants can link erosion processes across the landscape to small tributaries leading to larger bodies of navigable waters (Environmental Protection Agency 2005). One policy mechanism that has been implemented for some NPSP activities involves the regulation of total maximum daily loads in order to maintain water quality standards at or below threshold levels. TMDL’s can be monitored, yet it has proven difficult to discern and control the cause of excessive pollutant concentrations (Grismer 2013).

Best management practices (BMPs) provide an alternative and widely accepted water quality protection mechanism. BMPs were developed for major sources of NPSP which include urbanization, mining, agricultural, and silvicultural land uses. These BMPs were developed to protect water quality from NPSP and have been revised as new information and techniques have been developed regarding site-specific challenges and improvements in BMP application techniques or methods. In most southeastern states, forestry BMPs are voluntary, but in some states, such as Virginia, they are quasi-regulatory and fines may be imposed on loggers who do not implement appropriate BMPs and the improper implementation significantly impairs water quality (Cristan et al. 2016). Overall BMP implementation has been reported to be 86.4% in the northeastern U.S., 93.2% in the western U.S., and 92.4% in the southeastern U.S. (Cristan et al. 2018). Average statewide BMP implementation scores specifically for stream crossings in

Virginia have increased from 81% (2007) to 95% (2016) in the last decade (VDOF 2008; VDOF 2016a). The regional, state, and subcategory BMP implementation scores strongly suggest that BMPs are being implemented at satisfactory levels, yet direct linkages between BMP implementation levels and BMP effectiveness have not been fully documented for the southeastern region.

Numerous studies have shown that forest management is a sustainable land use when appropriate and adequate BMPs are used (Anderson and Lockaby 2011; Aust and Blinn 2004; Ice et al. 2010; Cristan et al. 2016; Shepard 2006). Although silvicultural operations typically produce low levels of sediment relative to other anthropogenic uses such as agriculture, urban development, and mining (Neary et al. 1989; Yoho 1980), some specific forest operations associated with access (roads, skid trails, stream crossings) have the potential to increase sedimentation if erosion control measures are not properly implemented (Aust et al. 2011; Brown et al. 2015). Logging disturbances that may increase soil erosion include compaction and removal of organic layers, and such disturbances can vary based on the silvicultural system and logging practices (Douglass 1975; Hood et al. 2002). Several studies have reported a decrease in hydraulic conductivity, an increase in bulk density, and a decrease in porosity, after the first few passes with harvesting machinery (Miwa et al. 2004; Parkhurst et al. 2018; Solgi et al. 2016). Soil compaction caused by intensive traffic can lead to low infiltration rates, and therefore increased overland flow, causing sheet and rill erosion. Thus, forestland managers must decide whether to build new roads or use legacy or spur roads that already provide access to the tract (Ice and Schilling 2012).

Streamside management zones (SMZs) capture and filter nutrients and sediment prior to entering streams below harvested tracts, however roads and skid trails may bisect and compromise the integrity of SMZs as necessary stream crossings are established (Aust et al. 2011, Lang et al. 2015). At such points sediment is easily transported in runoff to the stream. Furthermore, there is increased potential for road-stream surface and subsurface hydrologic connectivity, where subsurface flow is intercepted by the road and sheet flow results (Croke et al. 2005; Lakel et al. 2010; Lang et al. 2015; Megahan and Clayton 1983; Pechenick et al. 2014). Stream crossing approaches create an area where erosion and runoff have increased connectivity due to low ground cover, decreased surface roughness, channelized flow paths such as ditches, and absence of an SMZ in the actual crossing (Aust et al. 2011; Croke and Mockler 2001; Novotny and Chesters 1989).

Wade et al. (2012a) conducted a study in the southern Piedmont of Virginia and concluded that the minimum recommended skid trail BMPs (water bar) on bladed skid trails are less effective than slash or mulch-seed-grass cover treatments for reducing erosion. In a similar evaluation of overland skid trails on Piedmont sites, Sawyers et al. (2012) assessed skid trail closure costs and effectiveness. Mulch treatments were the most effective at reducing erosion, with hardwood slash providing the next best option. Wear et al. (2013) evaluated stream sedimentation at nine stream crossings in the Virginia Piedmont and evaluated cover BMPs on stream crossing approaches: slash only, grass seed/mulch, grass seed/mulch/silt fence. Both slash and grass seed/mulch treatments effectively reduced total suspended solids. In addition, they found that the silt fence worsened the site conditions and increase the stream sedimentation due to soil disturbance from installation techniques. These three studies generally supported the use of slash as an effective and cost effective option to close skid trails. Slash will provide immediate cover that lasts for several years whereas grass may not become established or may fail due to site conditions and season. Slash also hinders trespass by All Terrain Vehicles and is usually a less expensive cover BMP than seed and mulch, especially if the loggers can transport the material as part of the harvest (Cole et al. 2017).

BMPs are implemented by logging contractors and these expenses are commonly reflected in reduced stumpage payments to landowners. Thus, BMP implementations should be effective and cost effective so that financial implications are reduced for loggers, landowners, and the forest products industry. However, determinations of expenses associated with BMP implementation have been elusive because pricing for BMP implementation cost have been infrequently established and vary with equipment ownership, state standards, and regional soil and terrain circumstances (Montgomery et al. 2005). Landowners and/or loggers bear the initial BMP implementation costs, yet such costs may be passed on to landowners through lower stumpage prices (10%) and lost revenue through residual trees preserved for SMZs or wildlife (Kilgore and Blinn 2003; Lakel et al. 2006). Loggers experience equipment wear, extra time and operating expenses, and loss of productive monetarily rewarding operations by implementing BMPs, but such costs are not easily quantified. Conversely, loggers may also benefit from implementing BMPs by improving their operational planning (Shaffer and Meade 1997), enhancing their business advertisement and improving the overall societal perspective on forest management, as well as preserving forestland for future generations.

Costs of BMP implementation have been estimated through various economic analyses, engineering methods, and surveying techniques (Ellefson and Miles 1985; Cubbage 2004; Aust et al. 1996). These early studies found that as government regulation become increasing stringent, costs increased as well. Water bars were found to be the most expensive BMP treatment, which is now the minimum BMP required by the VDOF (Lickwar et al. 1992). Nonindustrial private landowners were found to spend more money on BMPs than industrial landowners due to the presence of steeper slopes and abundant waterbodies (Cubbage 2004). Aust et al. (1996) performed cost-benefit analyses for levels of BMP implementation, which ranged from \$0.79 to \$1.13 per ton of soil loss prevented. After reviewing several BMP cost studies, Cubbage (2004) concluded that BMP costs were reasonably within 1% to 5% of the gross harvest sale revenues.

Other BMP cost analysis includes the Virginia Tech Forest Road Costs Method (VTFRCM), which has been shown to estimate average costs for forest road construction and BMPs within 10% of the actual cost (Conrad et al. 2012). While the benefits of increasing BMP implementation increases relatively rapidly, the costs generally increase moderately until about the 92% level; the benefits reach a maximum and stabilize, while the costs continue to escalate (Aust et al. 1996; Cubbage 2004; Nolan et al. 2015).

2.2.2 Objectives

The literature indicates that stream crossings are potentially significant sources of sediment at stream crossings, yet the literature also establish that adequately implemented BMPs can reduce sedimentation. However, few studies have documented the influence of a varying level of BMPs on stream sediment across different physiographic regions. Furthermore, the literature indicates that BMP costs associated with increasing levels of BMP implementation at stream crossings are relatively undocumented. Therefore the objectives of this study are: 1) to assess and describe the relationships between BMP implementation in Virginia and erosion by modeling using the USLE-Forest and WEPP interfaces, 2) to explore factors that contribute to site-specific erosion processes during timber harvesting at stream crossings, such as road type and template, crossing structure, soil texture, cover percentages, and regional topography and logging practices, and 3) estimate the effects of enhanced BMPs on skid trail approaches by hypothetically enhancing the implementation levels and estimating the respective costs and benefits of doing so.

2.3 Materials and Methods

2.3.1 Site Selection

We sampled across three physiographic regions in Virginia: the Coastal Plain, Piedmont, and a consolidated Mountain region consisting of the Blue Ridge, Ridge and Valley, and Plateau physiographic provinces (Figure 2.1). The Virginia Department of Forestry (VDOF) permitted access to the state harvest database for all harvests completed in 2016. Subsequently, we contacted VDOF water quality specialists within each region so that they could specify which harvest sites had stream crossings. After we verified harvests that had stream crossings, we randomly selected at least 25 skid trail crossings per region (Mountains, Piedmont, and Coastal Plain), thus providing 79 total stream crossings across all three regions. All harvest sites were required to have been recent silvicultural operations (completed within the previous six months) that were eight hectares (20 ac) or larger. Sites with unusual conditions, such as land use conversions, were removed from the potential sample. Landowners were contacted to acquire permission to visit the sites. We subdivided the 25 regional samples across two time periods so that both wet and dry periods of the year were considered. Approximately ½ of the crossings (12-13) from each region represent harvests were harvested in January through June and the remaining 12-13 crossings from each region were harvests completed from July through December.

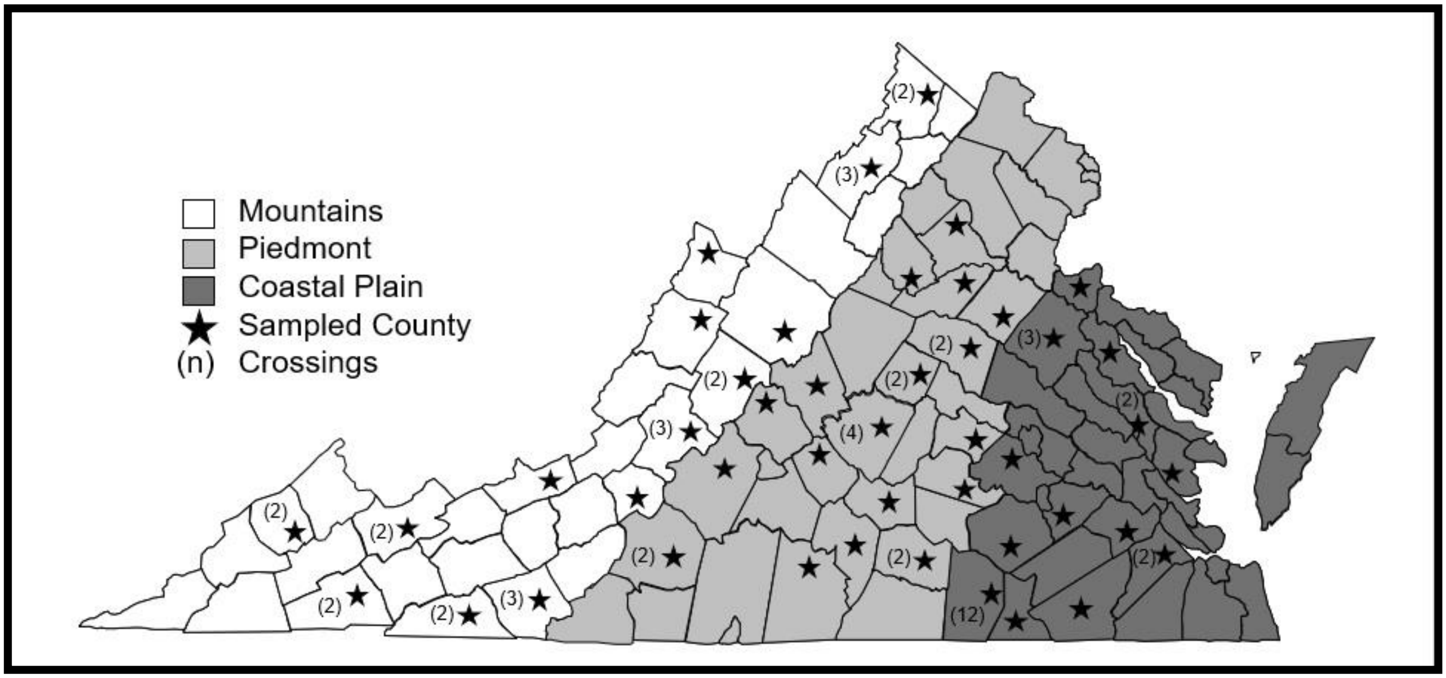

Figure 2.1. Map of the 45 sampled counties (79 skidder crossings) within Virginia's Mountain, Piedmont, and Coastal Plain regions.

2.3.2 Field Measurements

Sites were located using the latitude and longitude of the harvest landing provided by the VDOF. After the site entry and access were determined, we walked the site to locate stream crossings. Crossing locations were recorded with a Garmin Oregon 550t GPS unit and six to eight photographs were taken from various directions to document conditions for subsequent office analyses such as rating justifications. Stream crossing approach grades were measured with a clinometer and trail approach length and width were measured with a cloth tape. Each approach was defined as being between the area between the stream bank and the nearest upslope water control structure that was effectively draining water from the approach. If effective water control structures were nonexistent, the area continued to the nearest change in slope where water was no longer contributing to the stream crossing. Dimensions and characteristics of the stream crossing structure were measured and analyzed. Soil textures, which were used in subsequent erosion models, were determined in the field using texture-by-feel techniques and later compared to NRCS Web Soil Survey results. Ground cover and exposed soil were estimated as a percent based on walking across the trail on a zig-zag pattern and recording cover at each step, using a minimum of 20 steps as used on stream crossing approaches by Lang et al. (2017). Water control structures (water bars, water turnouts, dips) and soil cover/erosion control measures (slash, seed/mulch, hay bales, silt fences) were documented. These factors were considered for sub-rating the 1) drainage, 2) crossing structure, and 3) cover for each approach, and then an overall BMP rating was determined based on the majority of sub-ratings. In addition to this BMP rating, we also used the appropriate portions of the VDOF BMP audit (2014) to calculate a BMP implementation score that represents how VDOF BMP audits would rate BMP implementation at the crossing (Table 2.1). We included only those BMP audit questions that were applicable to the stream crossing being evaluated. We documented characteristics upstream and downstream of the crossing to classify the channel with the Rosgen system and noted any visible form of active sedimentation downstream of the crossing (Rosgen 1994). Overall, our methodology was similar to that used by Nolan et al. (2015).

Table 2.1. VDOF BMP Audit questions regarding stream crossings; **bolded** questions are most relevant and potentially correlate with erosion on approaches.

1. **Are approaches stable and unlikely to contribute sediment to the stream?**
2. Are culvert pipes installed properly in the channel to avoid undercutting and channel erosion?
3. Are culverts and bridges of adequate length?
4. Are culverts covered with adequate and appropriate fill material?
5. **Are culverts covered with gravel to reduce erosion near the stream? (crossing)**
6. Are culverts properly sized according the BMP manual Table 6 and 7 or Talbots formula?
7. **Are fords used only where a natural rock base (or geoweb) and gentle approaches allow?**
8. Are headwalls stabilized with vegetation, rock, or fabric to minimize cutting?
9. Are permanent bridge abutments adequate and stable?
10. **Are stream banks and approaches reclaimed with sufficient vegetation, rock or slash?**
11. **Are stream crossings installed at or near right angles where possible?**
12. Are temporary culverts, pole bridges, and bridges removed?
13. **Are water diversion structures present where needed on approaches?**
14. Do all ford crossings avoid restricting the natural flow of water?
15. **Do all ford approaches have a 50-foot approach of clean gravel?**
16. **Do all ford crossings have underlying geo-textiles where needed on approaches?**
17. Is the addition of unnatural materials in the stream to facilitate the use of a ford minimized?
18. Were pole bridges used only in appropriate circumstances?

2.3.3 BMP Rating

Previous studies have used a rating system (BMP-, BMP-standard, BMP+) to effectively assess the implemented BMPs on roads, skid trails, and stream crossings (Figure 2.2) (Nolan et al. 2015; Morris et al. 2016). Stream crossing approaches in this study that received a rating of BMP-standard met the recommendations of the VDOF state BMP manual. Crossings that received a BMP+ exceeded the recommendations of the manual, while BMP- ratings were given to the crossings that did not meet the minimum recommendations of the BMP manual. Ratings were determined by individually rating three categories that encompass the primary goals of the manual and finally choosing the rating with the majority. These categories address the presence and effectiveness of: 1) water control structures, 2) ground cover, and 3) crossing structure.

Ground cover has been proven effective at reducing erosion on forest roads, cut and fill slopes, and streambanks. While slope, approach length, microclimate, and soil texture can additionally impact erosion rates, establishing 40-50% ground cover has been shown to significantly reduce erosion, while 70-80% ground cover will effectively control erosion (Berglund 1978). This further supports our reasoning for using the BMP rating system; BMP-standard crossings had an average cover percentage of 63. BMP+ crossings had an average cover percentage of 93.

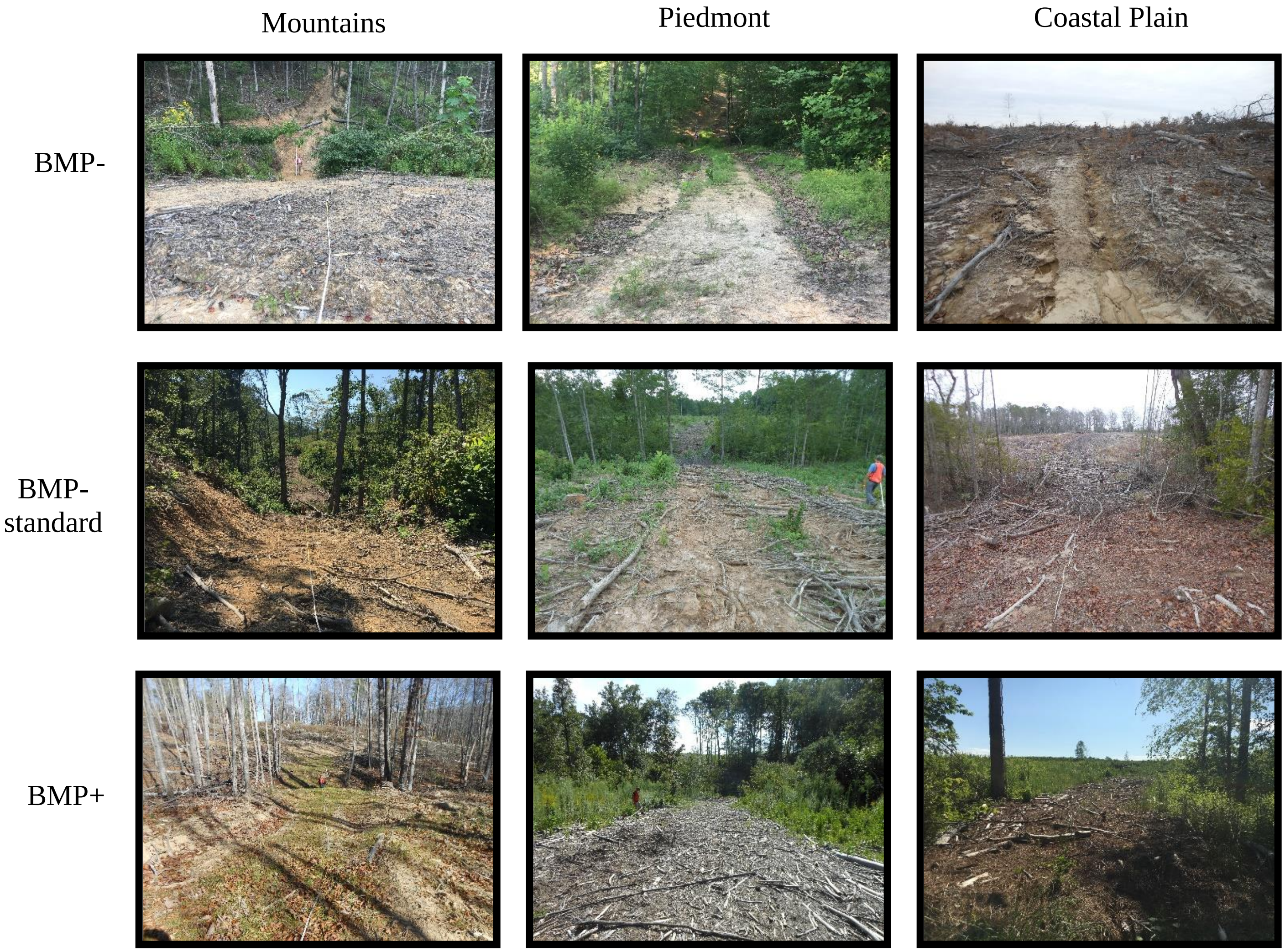

Figure 2.2. Representative skidder crossing approaches for each BMP rating category by region.

2.3.4 Erosion Models

Due to the large number of harvest sites to be evaluated it was infeasible to install either stream water sampling equipment or sediment traps, which have been used for studies having low numbers of samples. Rather we used two commonly used erosion models (Universal Soil Loss Equation modified for forestland (USLE-Forest) and Water Erosion Prediction Project (WEPP) that have been widely used on forest operations, including stream crossing approaches (Brown et al. 2013). Because stream crossings were assumed to be delivering all water to the stream, the estimated erosion is assumed to equate to the mass of sediment that enters the stream. Lang et al. (2017) conducted a study in the Mountains and Piedmont of Virginia and concluded that this is a valid assumption based on the proximity of approaches to the stream. Similar assumptions have also been used by Brown et al. (2013) and Wear et al. (2013).

The USLE-Forest (Dissmeyer and Foster 1984) was used to estimate potential erosion in megagrams/hectare/year that occurred on the left and right approaches to the stream, similar to the methods used by Brown et al. (2013), Wear et al. (2013), and Nolan et al. (2015). Within the USLE-Forest, the rainfall and runoff coefficient (R) was determined for each crossing using the isoerodent map from the USLE-Forest manual. Soil erodibility (K) values were acquired from the NRCS Web Soil Survey database (whole soil) regarding the soil series at the appropriate soil horizon depth at the crossing. The slope length and steepness factors (LS) were estimated based upon slope length, width, and slope percent in accordance with the LS methodology in the USLE-Forest manual. The cover and support practices (CP) factors encompass canopy cover (estimated with a concave spherical densitometer), percent bare soil and time since tillage, and amount of onsite storage. Storage coefficients were determined after visually examination for step effects, presence of invading vegetation, and type of ground cover. These R, K, LS, and CP estimates are multiplied to generate an estimated erosion rate for each approach. Potential erosion estimates were weighted by area and averaged for both crossing sides to develop an overall potential erosion and sedimentation rate for each crossing.

The Water Erosion Prediction Project (WEPP), developed by the USDA (Elliot et al. 1999), was used to compare 158 stream crossing approaches (2 approaches at 79 stream crossings) to the USLE-Forest model values. Stream crossing approaches were modeled using the WEPP:Road interface, and the soil loss values were recorded for comparison to the USLE values. Skid trail approaches were characterized as “Forest Bladed Road” in the management file, and “Disturbed Skid (clay loam, silt loam, loam, sandy loam)” in the soils file based on Web Soil Survey soil textures (Brown et al. 2013, Vinson et al. 2017a, Wade et al. 2012b). Climate files were created using the CLIGEN database from the nearest research station(s) to each site. Hillslope files were created based on the road template data collected in the field. Rock content, bulk density, and vegetation types were not manipulated due to a lack of field measurements for these parameters. It was beyond the scope of this project to attempt the laborious reprogramming and recalibration of the WEPP model, therefore the standard WEPP working files were left unmodified to best represent using the model as a management tool by BMP inspection personnel.

2.3.5 Data Analyses

Each BMP- crossing received two hypothetical BMP upgrades: first to BMP-standard and second to BMP+. All BMP-standard crossings received hypothesized upgrades to the BMP+ level. These upgrade processes involved identifying needed BMP improvements for each approach of the crossing. Hillslope length, soil depth, and cutbank depth typically explain much of the variation in road runoff prediction (Wemple and Jones 2003). The data resulting from the USLE-Forest model were used to support decisions regarding upgrades and evaluated the cost-benefit ratios. Based on our interpretations, the most feasible methods for reducing rates of erosion are reducing slope length and adding more cover to the approaches. Adding water control structures closer to the stream influences the LS factor in the USLE-Forest model, while adding cover will reduce the bare soil factor in the USLE-Forest model. Similarly, both of these factors were successfully manipulated to hypothetically reduce rates of erosion by Nolan et al. (2015). Major reconstructions of the road templates, which could theoretically reduce soil erosion, were not considered because major construction efforts were beyond the scope of the study. However, by implementing other alternatives like ripping and revegetating the trail surface, geomorphic effects such as fill slope destabilization and fine sediment delivery could be prevented (Wemple and Jones 2003).

Costs for hypothesized improvements, such as additional water control structures, were estimated using the Virginia Tech Forest Road Costs Method (VTFRCM) (Conrad et al. 2012). We supplemented the model with findings from other research projects. For example, Cole et al. (2017) estimated an average cost ($191.47) of slash application on 100 meters of trail after and during harvesting operations. These estimates were used in the cost analysis of slash application in this study. Seed and mulch application was determined using cost per kilometer and converting that to cost per square meter based on results by Sawyers et al. (2012) and Vinson et al. (2017b). Cost-benefit ratios were determined by dividing the cost of the improvement of a crossing by the change in erosion between the current and hypothetical erosion rates. This comparison allowed us to calculate the monetary value per mass ($/Mg) of sediment prevented from entering the stream.

2.3.6 Statistical Analyses

JMP-Pro 13 was used to perform all statistical analyses (SAS Institute, Inc., 2016). As is common for operational research, data were not normally distributed, thus we analyzed data with a combination of descriptive statistics and nonparametric analysis, supplemented by regression.

We determined means, medians, minimum, and maximum values for BMP levels within all regions and types of crossings, and we evaluated significant differences with nonparametric tests such as the Kruskal-Wallis test, followed by multiple comparisons using the Steel-Dwass all pairs test (Ott and Longnecker 2016). We also used regression to facilitate interpretation of the relationships between BMP implementation percentages and potential erosions rates.

2.4 Results and Discussion

2.4.1 BMP Implementation on Skid Trail Stream Crossings

In the Coastal Plain (57.1%) and Piedmont (64%) regions of Virginia, portable skidder bridges are the most common type of stream crossings (Table 2.2). Within the Mountain region, both portable bridges (34.6%) and pole bridges (50%) are used frequently. Fording a stream on a skid trail is not recommended by the BMP manual, as it violates the Virginia Silvicultural Water Quality Law, thus explaining why fords were not found on skid trail crossings. In the Mountains, where ephemeral draws are prominent, slash and or pole size material are sometimes used to allow passage over the small streams while not restricting the channel and such crossings were classified as pole bridges. Recently, portable bridges have been encouraged through VDOF cost share programs and the portable bridge program is evidenced in the distribution of crossings types. These portable bridges allow migration of aquatic species, limit the amount of sediment entering the stream during installation, and are cost effective due to the potential for multiple uses. Culverts have advantages of almost unrestricted weight limits and familiarity of installation but offer disadvantages to stream channel flows and sediment increases (Aust et al. 2003; Aust et al. 2011; Kidd et al. 2014; Morris et al. 2016).

Perennial and intermittent stream crossings are addressed specifically in the BMP manual regarding SMZ width, slope, and proper crossing structures. These streams are typically represented by solid or dashed blue line streams on topographical maps and have semi-permanent to permanent flow periodicities. These streams provide significant nexus points for larger navigable waterways and are protected by the Clean Water Act. Ephemeral drains are not addressed specifically in the manual because their flow is dependent on stormflow, however retired agricultural gullies, seeps, springs, and natural ponds are addressed as sensitive areas that may require an SMZ and other BMPs. SMZs are recommended for ephemeral drains with evidence of channel scour, however such drains do not provide habitat to aquatic species (VDOF 2011). Some studies have shown that ephemeral streams have the potential to rapidly move sediments and nutrients that have not been filtered through an SMZ (Neary et al. 2010; Witt et al. 2013).

For all types of skidder crossings, 41.8% exhibited visual evidence of active sedimentation downstream. Of culvert crossings used on skid trails, 50% had evidence of active sedimentation downstream, while only 16.7% of pole crossings and 9.8% of portable bridge crossings showed evidence of active sedimentation. These observations were based on the presence/absence of obvious sedimentation (e.g. sediment transport pathways, SMZ breakthroughs, rills) and do not quantify the sediment observed. Furthermore, other factors such as time after harvest, streambank conditions, recent rainfall, and/or stream geomorphology could affect such observations. However, the observational differences between the crossing types support findings by Morris et al. (2016) and Aust et al. (2011) which also found that bridges result in lower sedimentation rates than culverts or pole bridges. These data may also support the use of additional BMPs for erosion control at skid crossings, particularly when culverts are used.

Table 2.2. Distribution of crossing structures used on skid trails by region.

	Culvert		**Pole Crossing**		**Portable Bridge**		**All Crossing Types**	
	N	% within region	N	% within region	N	% within region	N	% of total
Mountains	4	15.4%	13	50.0%	9	34.6%	26	100.0%
Piedmont	3	12.0%	6	24.0%	16	64.0%	25	100.0%
Coastal Plain	1	3.6%	11	39.3%	16	57.1%	28	100.0%
Total	8	10.1%	30	38.0%	41	51.9%	79	100.0%

The Mountain region had significantly lower BMP audit score means as compared to Coastal Plain region (p=0.008), but other comparisons among regions were not significant (p=0.5386; p=0.1488). There were no significant differences among BMP audit scores by region by BMP rating (Table 2.3). Distributions were generally similar in rating categories. The overall average BMP audit score regarding skidder stream crossings was 88%. This complements the most recent BMP survey provided by Cristan et al. (2018) the Southeastern average for BMP implementation was reported 92.4%, and the national average 91%. Virginia state score for overall BMPs was similar but slightly lower at 89.9% and Virginia's score for stream crossings was 92%.

Audit scores were dramatically impacted by the water control/question 13, which regarded the sufficiency of water control, in the BMP audit in all regions. Stream crossings sometimes did not comply with the standard water control recommendation due to inappropriate distances or absence of structures in the Coastal Plain (17.86%), Piedmont (16%), and Mountains (46.1%). Stream crossing approach stability was found to be 100%, 76%, and 73% stability in the Coastal Plain, Piedmont, and Mountains, respectively. Question 10, regarding stabilized streambanks with vegetation or slash, had a negative impact on audit scores by 15.4% in the Mountains, 16% in the Piedmont, and 3.6% in the Coastal Plain.

Table 2.3. Distribution of audit scores by BMP rating and region. Values not followed by the same letter within a column specific to a region are significantly different using the Steel-Dwass All Pairs test at α = 0.05.

Region	BMP Rating	N	Mean	Median	SD	Min	Max
Mountains	BMP-	2	54.9	54.9a	17.1	42.8	67
	BMP_std	21	83.4	85.7a	16.2	33	100
	BMP+	3	96.7	100a	5.8	90	100
Piedmont	BMP-	3	51	50a	31.5	20	83
	BMP_std	14	88.7	87.9a	12.4	60	100
	BMP+	8	95.7	100a	8.1	80	100
Coastal Plain	BMP-	1	50	50a	-	50	50
	BMP_std	14	93.1	100ab	8.4	80.0	100
	BMP+	13	98.9	100b	4.0	85.7	100

We used two soil erosion models, the USLE-Forest and WEPP. Both models have been used in similar applications, yet neither has been shown to be clearly superior, thus justifying the use of both models. USLE-Forest and WEPP were both initially intended for agricultural use, but have been modified in order to capture the attributes of undisturbed forest, harvesting conditions, and post-harvest recovery phases. Our study did not directly measure actual sediment yield from the sites, therefore we did not verify the model versus measured erosion models. However, several studies in the regions (Brown et al. 2013; Wade et al. 2012b; Vinson et al. 2017a) have compared the efficiencies and accuracy of these two programs and found both to be generally satisfactory for treatment comparisons. We used USLE-Forest erosion rates to estimate effects of BMP upgrades and assign costs to the BMPs implemented in the hypothetical enhancements. WEPP estimates tended to have higher mean and median values that those of USLE, but provides a more conservative approach for the extreme values compared to USLE (Table 2.4). WEPP was also not able to differentiate erosion rate differences between BMP ratings as efficiently as the USLE. This might be due to the minimal manipulation of WEPP files within the program for this study. Vinson et al. (2017a) concluded that interior file adjustment is often necessary in order to achieve better accuracy with the WEPP program and that unadjusted standard WEPP consistently performs less accurately than the USLE model.

There were no significant differences in erosion rates by region as estimated by the USLE (p=0.2657) or WEPP (p=0.2557) models. Skid trails stream crossing approaches had potential erosion rates ranging from <0.2 to 117.7 megagram/hectare/year as modelled by the USLE-Forest. As BMP implementation levels increased (based on audit scores), potential erosion rates decreased significantly (Figure 2.2). Audit scores were adjusted to perform the regression analysis to include only the questions that pertained to erosion on the approaches. This better represented the effects of BMP implementation on approaches and its influence on erosion rates. Questions regarding crossing structures sizing and placement, removal, or stability were removed for the regression (Table 2.1; Figure 2.2). Both the original and adjusted graphs are shown (Figure 2.2).

Table 2.4. Summary statistics for erosion rates and audit scores by region. Values not followed by the same letter within a column are significantly different using the Steel-Dwass All Pairs test at α = 0.05.

	Mean	**Median**	**SD**	**Min**	**Max**
BMP Audit Score (%)					
Mountains	82.7	85.7a	17.6	33	100
Piedmont	86.4	90ab	19.3	20	100
Coastal Plain	94.3	100b	11.2	50	100
USLE-Forest Erosion Rate (Mg/ha/yr)					
Mountains	11.9	2.2a	26.4	0.0	117.8
Piedmont	8.2	1.0a	15.2	0.0	69.0
Coastal Plain	6.8	0.4a	16.3	0.0	72.1
WEPP Erosion Rate (Mg/ha/yr)					
Mountains	17.8	12.8a	16.6	1.5	68.4
Piedmont	23.6	18.8a	19.5	1.6	76.1
Coastal Plain	14.2	11.6a	11.1	1.5	48.4

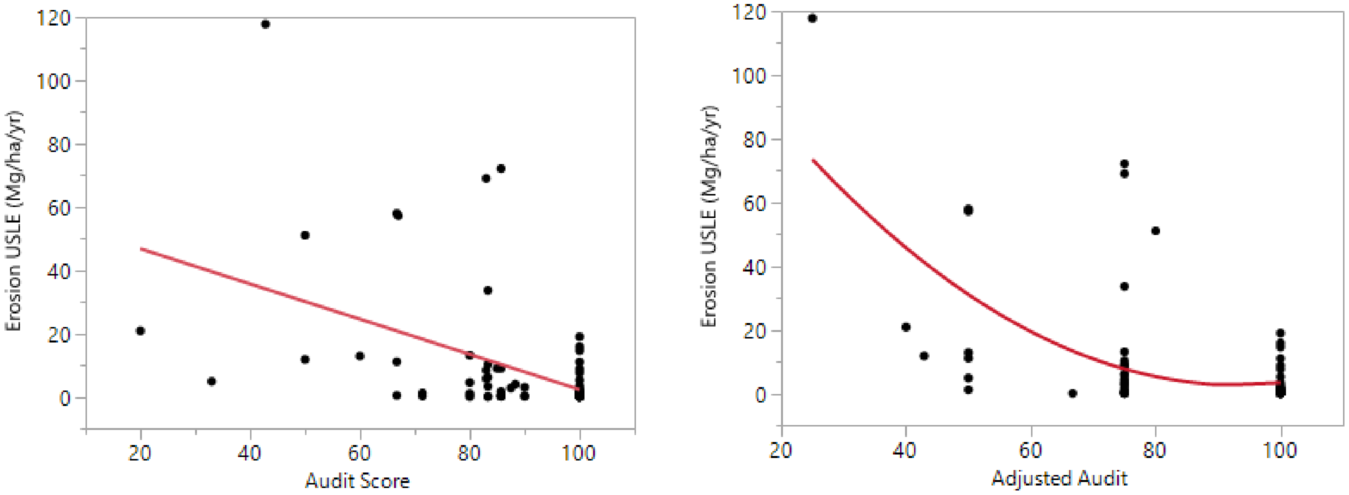

Figure 2.2. Erosion rate as a function of BMP audit score. Left: original audit score (r^2= 0.22, F = 22.11, p <0.0001). Right: adjust audit score to reflect erosion control BMPs (r^2= 0.36, F = 21.00, p <0.0001).

Water control structures and cover percentages were evaluated on each approach to the 79 stream crossings and were subsequently analyzed separately for a total of 158 skidder crossing approaches. Individual ratings for the water control and cover subcategories were used in this analysis to better understand the distributions of BMPs used. Analyses were limited to presence/absence of structure or cover and could not account for better or worse implementation on specific sites. Water controls measures were documented only if the structures were properly diverting runoff away from the stream and into the SMZ. For example, if an approach had a failed water bar, this structure would not be included in the determination of slope length and would be listed as “none” for structure.

Applications of slash were the most common water control techniques used on skid trail stream crossing approaches in the Coastal Plain (41.4%) and Piedmont (42.3%). Slash applications were documented in instances where slash applications were of sufficient depth and sufficient soil contact to act as a water diversion for runoff and as filtering structures that retained sediment. In the Mountains, water bars were used most frequently (33.3%) (Table

2.5a). Slash applications are less frequently used in the mountains due to the application constraints of hardwoods slash as well as restrictions associated with cable skidders (Barrett et al. 2017). Stream crossing approaches in all three regions were significantly deficient in water control (Table 2.5a).

Data were categorized by BMP category and the majority of BMP+ crossings used slash (52.2%) (Table 2.5b). Slash is often considered a less expensive alternative to constructing water bars, is effective for meeting BMP water control standards and provides long lasting cover. In contrast, the majority (91.3%) of skidder approaches in the BMP- category used no form of water control.

The use of slash as ground cover dominated the Coastal Plain (75.0%) and Piedmont (63.8%) regions, and was used on 21.2% of the Mountain approaches (Table 2.6a). Grass, mulch, and various combinations of grass, mulch, slash, logs, and other vegetation were used evenly in the Coastal Plain and Piedmont, while the mountains relied much more heavily on grass seed and mulch than slash. Slash was used on 61.6% of the BMP+ crossings, with insignificant differences between other ground cover types (Table 2.6b).

Table 2.5a. Distribution of water control structures by region (based on 158 skidder approaches).

	Slash dam	Rolling dip	Sediment pool	Tank trap	Water bar	Water turnout	None
Mountains	3.5%	1.8%	0.0%	1.8%	33.3%	12.3%	47.4%
Piedmont	42.3%	1.9%	0.0%	0.0%	23.1%	5.8%	26.9%
Coastal Plain	41.4%	0.0%	1.7%	0.0%	25.9%	6.9%	24.1%

Table 2.5b. Distribution of water control structures by BMP rating for drainage sub-category (based on 158 skidder approaches).

	Slash dam	Rolling dip	Sediment pool	Tank trap	Water bar	Water turnout	None
BMP-	0.0%	0.0%	0.0%	0.0%	0.0%	8.7%	91.3%
BMP-standard	29.8%	1.7%	0.8%	0.8%	33.1%	7.4%	26.4%
BMP+	52.2%	0.0%	0.0%	0.0%	26.1%	13.0%	8.7%

Table 2.6a. Distribution of cover types by region (based on 158 skidder approaches).

	Chips	Grass	Gravel	Logs	Mulch	Natural veg or rock	Seed and mulch	Slash	None
Mountains	3.0%	30.3%	4.5%	6.1%	15.2%	10.6%	6.1%	21.2%	3.0%
Piedmont	0.0%	5.8%	1.4%	10.1%	2.9%	10.1%	5.8%	63.8%	0.0%
Coastal Plain	0.0%	7.8%	3.1%	3.1%	6.3%	0.0%	0.0%	75.0%	4.7%

Table 2.6b. Distribution of cover types by BMP rating for ground cover sub-category (based on 158 skidder approaches).

	Chips	Grass	Gravel	Logs	Mulch	Natural veg or rock	Seed and mulch	Slash	None
BMP-	6.7%	13.3%	20.0%	13.3%	6.7%	20.0%	0.0%	13.3%	6.7%
BMP-standard	2.6%	18.4%	5.3%	5.3%	2.6%	13.2%	10.5%	36.8%	5.3%
BMP+	0.0%	13.7%	0.7%	6.2%	9.6%	4.1%	2.7%	61.6%	1.4%

2.4.2 Hypothetical Upgrades and Costs

Predicted erosion rates on skid trails were reduced by an average of 31.6 megagram/hectare/year when upgrades were made from BMP- to BMP-standard. Upgrades from BMP-standard to BMP+ further reduced potential erosion by an average of 7.0 megagram/hectare/year. Average erosion rates and costs by region and BMP rating are presented in Table 2.7. Average costs to upgrade a skidder stream crossing approach rated as BMP- to a BMP-standard was $36.00, with a range of $4.58-$50.18. Costs to upgrade a BMP-standard to a BMP+ averaged $62.23, with a range of $18.75-$249.00. The Mountain region had lower costs per unit of erosion reduction due to BMP upgrades with lower costs than the other regions; improving BMP- sites to BMP-standard in the Mountains would have an average cost of $13.59/Mg of erosion reduced.

Our data indicate that relatively small expenditures per crossing could allow stream crossing approach BMPs to exceed the BMP manual recommendations. However, the general trends revealed by the cost-benefit ratios indicate that expenditure required to develop BMP+

levels do not prevent a significant amount of erosion, indicating that BMP-standard expenditures are more cost effective. In this situation where the absolute costs are relatively low, it is possible that many loggers would be willing to investment slightly more in BMP+ level expenditures at the relatively low numbers of stream crossings simply to ensure that they satisfy water quality inspections and enhance the professional appearance of the harvest. Furthermore, our data indicate that implementation of the recommended BMPs protects water quality. This additionally implies that major additional BMP expenditures will not be passed along to landowners, so they will not receive reduced stumpage prices and they will still own property protected against sedimentation and erosion. Skid trails stream crossings are relatively inexpensive to close and remediate with slash and water bars. Such sites will potentially recover quickly, establish seed, and trap sediment because traffic has been stopped completely, unless the site is still open to recreational activities (Cook and King 1983; Brown et al. 2013; Vinson 2017b).

Some limitations of our project were revealed after reflection. As with other observational and operational studies, some factors were not accounted for in our data collection. For example, some landowners denied permission for property visitation and therefore we do not have a totally random sample. Also, we visited some sites that were reported to have a stream crossing by the VDOF, yet we failed to find a crossing. In some instances we believe the stream crossing was on an access road to the operation, yet was not actually part of the operation. Finally, some landowners elect to use the skid trails for access after the skid trails have been closed. Post closure recreational traffic activities after post closure can negate some types of BMPs and such use biases BMP effectiveness. Despite these limitations we believe that we have captured a range of BMP levels and documented the effects of increasing BMP use on both stream sedimentation and implementation costs.

Table 2.7. Erosion rates before and after hypothetical upgrades and the respective costs for skid trail stream crossings.

	N	Average Before Upgrade (Mg/year)	Average After Upgrade (Mg/year)	Average Upgrade Cost ($/crossing)	Average Upgrade Cost/Benefit Ratio ($/Mg)
Mountains					
BMP-	2	3.15	0.44	36.84	13.59
BMP_std	21	0.14	0.03	58.80	534.55
Piedmont					
BMP-	3	1.64	0.29	46.03	34.10
BMP_std	14	0.22	0.03	61.67	324.58
Coastal Plain					
BMP-	1	0.33	0.21	4.58	38.17
BMP_std	14	0.46	0.04	68.12	162.19
BMP-	**6**	**1.93**	**0.33**	**36.06**	**22.54**
BMP-std	**55**	**0.25**	**0.03**	**62.23**	**282.86**

2.5 Summary and Conclusions

This study supports the recommended implementation of forestry best management practices and confirms that there is valuable erosion control resulting from the application of standard BMP manual recommendations. BMPs are best utilized as preventive techniques to control erosion, rather than a mitigation procedure after severe damage has occurred. This means implementation of BMPs should be planned before harvest and implemented during the harvest operations rather than applying BMPs after operations are complete. Communications between the logging professionals and VDOF BMP inspectors are important during post-harvest stabilization and restoration. The majority (79.22%) of properties that we sampled were owned by private individuals or families, while 19.48% were considered to be industry or corporate REITs and TIMOs, based on the VDOF classification system. This further emphasizes the importance of land management training for individuals that may lack professional staff foresters as tract size decreases over time with increasing fragmentation, population growth, and urban development.

Regionally, while choices in water control structures and cover types varied, potential erosion rates after six months of stabilization were not statistically different. This confirms that while some BMPs may be more cost effective than others, if correctly implemented, erosion over time is controlled. Questions regarding BMP implementation and regulations interpreted from the Clean Water Act still persist regarding ephemeral channel BMPs, headwater SMZ efficiency, and specifications for water control construction.

In summary, we have identified several specific findings and recommendations based on our research.

1. Skidder bridges resulted in the lowest level of observed sedimentation from any stream crossing type, while culvert crossings tended to provide more visual evidence of stream sedimentation. This is consistent with findings from Aust et al. (2011) and Morris et al. (2016) and further indicate that stream crossing selection can influence sedimentation.
2. Overall, stream crossings for skid trails in the mountains tended to use stream crossing options that favored sediment production while implementing lower levels of BMP implementation for water control and cover. Logging contractors and landowners mountain region might benefit from additional BMP training workshops. We recommend the VDOF look into alternative BMPs specific for the Mountain region in Virginia.
3. Slash applications were the primary form of ground cover used on skid trails upon closure in the Coastal Plain and Piedmont. Slash was also the most abundant ground cover on crossings that were rated BMP-standard or BMP+. Overall, slash is an efficient and cost effective mechanism for erosion prevention mechanism for skid trail stream

crossing closure as supported by the research of Wade et al. 2012a, Sawyers et al. 2012, and Vinson et al. 2017b.

4. As BMP implementation increased, potential erosion rates decreased. Therefore we conclude high levels of BMPs implementation suggest corresponding levels of water quality protection from sediment. This conclusion is also supported by the recent watershed BMP implementation research by Xu and Xu (2018).
5. The additional costs to meet or exceed the standard BMP recommendations in the VDOF BMP manual are relatively low compared to typical logging expenses. The cost-benefit ratio to reduce one megagram of erosion at the crossing, moving from a BMP- to a BMP-standard, is reasonable in every region. Therefore, we conclude that BMP implementation at recommended rates provides acceptable levels of sediment protection. Exceeding manual requirements appear to be unwarranted in many instances, but should be considered in erosive areas, ecologically sensitive areas, highly trafficked trails, or in specific situations where there has been severe disturbance from logging practices.

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3.0 EVALUATION OF BEST MANAGEMENT PRACTICES AT FOREST ROAD STREAM CROSSINGS IN VIRGINIA

3.1 Abstract

Forestry best management practices (BMPs) guidelines focus on protecting water quality by minimizing soil erosion and sedimentation. Potential for erosion from forest operations is elevated during road construction and usage, with heightened potential for sediment delivery at stream crossings. This study quantifies and evaluates BMP implementation and effectiveness at randomly selected forest road stream crossings in Mountains, Piedmont, and Coastal Plain regions of Virginia. Data from 75 crossings were used to model erosion from stream crossing approaches using the Universal Soil Loss Equation for forestry (USLE-Forest) and the Water Erosion Prediction Program (WEPP:Road). Crossings were rated as BMP-, BMP-standard, or BMP+ based on quality of road templates, road drainage, ground cover, and stream crossing structures. Relevant questions from the Virginia Department of Forestry (VDOF) BMP audit were also used to score stream crossings. Potential costs for upgrading the crossing to an improved BMP category were estimated by adjusting ground cover percentage and approach length, and subsequently applying the Virginia Tech Forest Road Costs Method. Results indicate that erosion rates decrease as BMP implementation increases ($p < 0.05$). Crossings that received BMP-standard and BMP+ ratings made up 83% of the crossings sampled, with an average erosion rate of 6.8 megagrams/hectare/year. Hypothetical improvements beyond standard BMP recommendations (BMP-standard) provided minimal erosion prevention relative to increased costs.

KEY TERMS: best management practices; erosion; forest roads; nonpoint source pollution; stream crossings; forest harvesting

3.2 Introduction

Forested watersheds are widely acknowledged to be outstanding sources of clean water and forest management within such watersheds has been shown to be compatible with clean water supplies (Ice 2004). However, forest management activities that reduce ground cover, increase connectivity to streams, and otherwise increase erosion and sediment delivery can decrease water quality (Croke and Hairsine 2006). Forest management activities such as construction and use of roads, skid trails, and stream crossings to access timber for harvesting, reduce fuels, and provide recreation have been shown to increase sedimentation rates if water quality protection measures, known as best management practices (BMPs), are not adequately implemented (Aust and Blinn 2004).

Forest access features (roads, trails, decks, stream crossings) have been found to contribute 90% of all soil erosion on forested lands (Hoover 1952; Yoho 1980; Germain and Munsell 2005). If eroded soil is detached and transported by natural hydrologic processes like precipitation, seepage, or runoff, and is deposited in waterbodies, it is categorized as stream sedimentation, which is considered a nonpoint source pollutant (U.S. Environmental Protection Agency, 2017. Polluted Runoff: Nonpoint Source Pollution. Accessed January 2018, https://www.epa.gov/nps/what-nonpoint-source). Nonpoint source pollutants are not readily attributable to specific sources, therefore they are most often addressed through the use of best management practices (BMPs) for forest operations (Boston 2012).

BMP implementation rates average 92.4% in the southern U.S. (Cristan et al. 2018). In Virginia, the mean implementation score specific to stream crossing BMPs for forest roads is 95% (VDOF 2016a). While silvicultural activities are currently exempt from the point source National Pollutant Discharge Elimination System (NPDES) permitting requirement, forest operations have been reviewed by the Supreme Court of the United States for point source discharge from forest road ditches. Such scrutiny emphasizes the need for addressing potential BMPs to minimize pollution at stream crossings.

The literature regarding forest road erosion concludes that best management practices are effective at reducing runoff and sedimentation (Aust and Blinn 2004; Jackson et al. 2004). However, effects of differing levels of BMP implementation on erosion and sediment delivery are not well established and quantification of BMP effectiveness is desirable (Anderson and Lockaby 2011; Ice and Schilling 2012). Such documentation can aid forest landowners, logging contractors, and forest managers in their efforts to identify areas in which BMP implementation could be efficiently targeted and such information could help state agencies in efforts to document the effectiveness of state and federal BMP programs.

3.2.1 Forest Roads

Road construction and maintenance may increase erosion potential due to removal of ground cover, soil compaction, altered soil structure, concentration of flow on surfaces and in ditches, interception of subsurface flow by the road prism, and increased slopes (Grace 2002). These conditions facilitate detachment and transport of soil particles. Detached and transported soil may be intercepted by the forest floor or it may be delivered to surrounding waterways, where such sediment can harm wildlife habitat and degrade water quality (Williams et al. 1999). Roads built prior to environmental regulations such as the Clean Water Act were often constructed with lower standards and could have more negative potential water quality impacts. Current land managers incorporate BMPs that encompass environmental sensitivity, aesthetics, and sustainability into road design, which reduce sedimentation rates, yet increase the construction costs of roads substantially (Grace 2002; Keller and Sherar 2003; Edwards et al. 2016).

Road sediment delivery is affected by multiple and potentially interacting factors. Road gradient and surface area influence the immediacy and volume of runoff, which therefore effect erosion processes. Precipitation and traffic are two factors that substantially influence sediment delivery rates (Bilby et al. 1989). Increases in slope and traffic have been found to increase erosion rates (Sheridan et al. 2006; Sugden and Woods 2007). As few as 20 passes by logging trucks can generate the same amount of erosion as that of a lightly trafficked road surface over one year (Coker et al. 1993). Some studies have found slope variation to account for 98% of erosion (Beasley et al. 1984) and others have shown that road gravel levels can reduce sediment delivery by over seven-fold (Brown et al. 2013). Forest roads can produce sediment yields 50% above pre-treatment values up to 15 years post-harvest (Swank et al. 2001).

3.2.2 Best Management Practices

Best management practice guidelines developed by all southeastern states address the importance of diverting overland flow to the forest floor. Streamside management zones (SMZs) provide an erosion buffer that is located between harvest disturbances and the streams in order to filter eroded soils before they can enter streams (Jackson et al. 2004; Ice and Schilling 2012). Compromised SMZs tend to occur in areas with steep slopes, low surface cover, and large contributing areas (Rivenbark and Jackson 2004; Lang et al. 2015). The forest floor has a limited trapping capacity, and sloping roads need to have proper water control structures and appropriate ground cover to slow water velocity and disperse flow gradually to the surrounding landscape. Grace (2002) studied the effectiveness of ditches treated with natural vegetation, riprap, silt fences, and sediment pools. He found that sediment pools were effective at trapping sediment until large rain events cause them to overflow. Riprap was much less effective at reducing runoff than vegetation. The study concluded that roads must undergo sufficient maintenance to adequately control erosion. Lang et al. (2015) performed another evaluation of road ditch BMPs and found that erosion mats with seed incorporated were the most cost effective ditch BMP for trapping sediment.

Canopy cover and ground cover diminish the effects of rainstorm energy on soils. Foltz et al. (2009) analyzed components of soil erosion and concluded that the presence of vegetated cover was more significant than traffic, soil properties, and surface preparation because vegetative cover trapped soil particles with roots, surface roughness, and higher infiltration rates. Brown et al. (2013) evaluated non-vegetative cover and determined that sufficient gravel cover on stream crossing approaches can significantly reduce erosion compared to that of bare approaches. They concluded that improper water control structures and/or insufficient ground cover caused the highest rates of sedimentation. To reduced gravel material and application costs, water control structures should be used to shorten the approach length that requires cover (Brown et al. 2015). Appropriately implemented BMPs have been shown to reduce stream sediment concentrations by 52-94% (Edwards and Williard 2010).

3.2.3 Stream Crossings

Stream crossings consist of both the road approach and the structure. Stream crossing structures can affect the rate of erosion at a stream; culverts introduce significantly more sediment into a stream during the installation and harvest phases of an operation than a bridge or ford (Aust et al. 2011; Morris et al. 2016). As long as sufficient maintenance is performed, erosion tends to decline as roads age; anomalies usually occur due to mass failures of culverted stream crossings (Elliot et al. 1994; Fransen et al. 2001). Bridges better maintain the natural stream channel and typically produce the least stream sediment during construction; however, permanent bridges can be the most expensive crossing type considered (USEPA 2005). The cost per use of a bridge is reduced when portable temporary bridges are used. Morris et al. (2016) evaluated in-stream sediment concentrations and found that the lowest level of BMP bridge treatment (BMP-) was still a better BMP option than the higher BMP levels used with culvert and ford stream crossings tested. Bridges are less commonly used on permanent truck roads, but they are good options for temporary truck roads. Although stream crossing type can affect sediment delivery, Aust et al. (2011) found that stream crossing approach conditions have greater potential to affect sediment delivery. After rainfall simulation studies on reopened legacy roads, Brown et al. (2015) found that poor location and/or water and grade control and cause sedimentation to be more pronounced in smaller streams. The results indicated that completely graveled approaches yielded 7.5X less sediment than bare approaches. Improper crossing structures and/or insufficient ground cover caused the highest rates of sedimentation.

3.2.4 Costs

The immediate responsibility of BMPs are most commonly addressed by the logging contractor completing the harvest, but BMP costs are also dispersed to landowners in the form of reduced harvest profits and to the manufacturing facilities in the form of increased raw material costs. Costs to implement BMPs include materials, machinery, and labor required, as well as the potential loss in productivity due to extended time spent constructing structures such as water bars and turnouts, applying ground cover, and removing debris from stream (Kilgore and Blinn 2003; Montgomery et al. 2005). A recent study in the northeastern U.S. estimated BMP implementation costs to range from $0-62/acre, and cause 0-20% loss in forest operations productivity (Kelly et al. 2017). BMP costs can vary by region, due to crew size and equipment, topography, soil type, and climate. Several evaluations of the costs and benefits of increasing BMP implementation have concluded that benefits reach a plateau and stabilize while the costs continue to escalate (Aust et al. 1996; Cubbage 2004; Nolan et al. 2015). Morris et al. (2016) performed a rainfall simulation experiment on three stream crossing structures at three levels of BMP implementation. Respective costs for bridge BMP installations were $5,368 (BMP-), $5,658 (BMP-std), and $5,858 (BMP+); the culvert BMPs cost $3,568 (BMP-), $4,166 (BMP-std), and $4,595 (BMP+); and the ford BMPs cost $180 (BMP-), $420 (BMP-std), and $1,903 (BMP+). They concluded that standard BMP levels effectively reduced stream sediment while minimizing costs.

3.2.5 Objectives

The literature clearly indicates that stream crossings are major potential sediment delivery points from forest roads and that BMPs can be used at such crossings to protect water quality. However, the literature does not adequately document the potential effects of differing levels of BMP implementation on sediment delivery, nor does it evaluate the effects of BMP implementation levels on costs. Therefore, the objectives of this study are to quantify the potential sediment delivery from different levels of BMP implementation and to estimate BMP implementation level costs at truck road stream crossings for the Mountain, Piedmont, and Coastal Plain regions of Virginia.

3.3 Materials and Methods

3.3.1 Site Selection

We randomly sampled 25 truck road stream crossings from 2016 harvest sites having stream crossings within the Coastal Plain, Piedmont, and Mountains regions (Blue Ridge, Ridge and Valley, and Alleghany Plateau) of Virginia (75 total crossings) in order to encompass the variance in geology, topography, and logging practices (Figure 3.1) (Barrett et al. 2017). The Virginia Department of Forestry (VDOF) provided access to the state harvest database for all harvests completed in 2016. The sample population was further stratified by VDOF water quality specialists from each region who identified which harvests used stream crossings. Other qualifying criteria included silvicultural operations, which eliminated land use conversions to pasture or urban development; tracts were at least eight hectares (20 ac) in size; and harvests had been officially closed out by the VDOF within the previous six months. We contacted all landowners in order to acquire sampling permission. We collected data during two phases to accommodate field seasons and capture effects of climate throughout the year. Approximately ½ of the crossings (12-13) from each region were sampled from harvests completed during the first six months of the year (January-June 2016), and the remaining sites were sampled (12-13) from harvests completed from July through December.

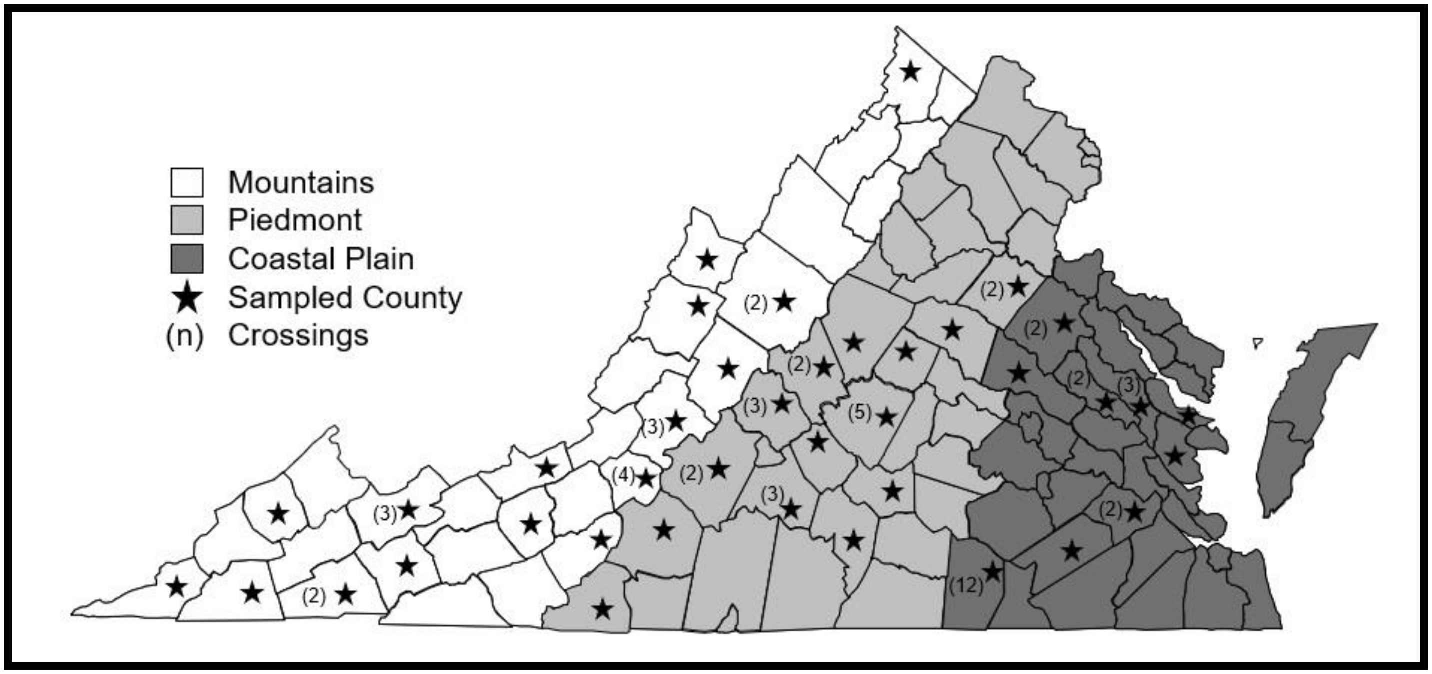


Figure 3.1. Counties in which truck road stream crossings were sampled from the three regions of Virginia.

3.3.2 Field Measurements

Harvest landing/log deck GPS coordinates were provided by the VDOF and were used to locate sites. Roads and skid trails were walked in order to locate stream crossings. Six to eight digital photographs were taken at each crossing from various directions and one central GPS point was recorded with a handheld GPS unit. Photographs and GPS coordinates allowed subsequent office examination and documentation of watersheds, conditions of approaches, streambanks, and stream rating justifications. Each road approach to the stream crossing was defined as being between the nearest stream bank of the crossing and the nearest upslope water control structure or nearest change in slope where water was no longer contributing to the stream crossing. A clinometer and 100-foot tape were used to measure approach grade, length, and width. Dimensions and characteristics of the stream crossing structure were measured and compared to BMP manual recommendations (VDOF 2011). Soil textures were determined in the field using texture-by-feel techniques and subsequently compared to NRCS Web Soil Survey results. Ground cover and bare soil percentages were estimated by walking across the road in a zig-zag pattern and recording cover at each step (covered steps/total steps)*100 = percent ground cover). Water control structures (water bars, water turnouts, dips) and erosion control measures (gravel, slash, seed/mulch, hay bales, silt fences) were evaluated. An overall BMP rating was determined based on an evaluation of sub-rating categories, which were: 1) road template, 2) drainage, 3) crossing structure, and 4) cover for each approach. We also used the portions of the VDOF BMP audit that were specific to stream crossing approaches (2014) to calculate a BMP implementation score (%) (Table 3.3). We included only BMP audit questions that were applicable to the stream crossing being evaluated, as was done previously in a related study by Nolan et al. (2015). We documented characteristics upstream and downstream of the crossing to classify the channel with the Rosgen system and noted any visible form of active sedimentation downstream of the crossing (Rosgen 1994).

Potential erosion rates for each approach to the stream crossing were estimated in megagrams/hectare/year using the Universal Soil Loss Equation modified for forestland (USLE-Forest) (Dissmeyer and Foster 1984), similar to the methods used by Brown et al. (2013), Wear et al. (2013), and Nolan et al. (2015) to evaluate stream crossings. The close proximity between approaches and crossings allowed us to assume that estimated erosion rates of the stream crossing approaches approximated the amount of sediment that reaches and enters the stream, as was suggested by Lang et al. (2017). Within the USLE-Forest erosion model, the rainfall and runoff coefficient (R) was chosen for each crossing using the isoerodent map from the USLE-Forest manual. Soil erodibility (K) was acquired from the NRCS Web Soil Survey database (whole soil) regarding the soil series at the exposed soil horizon depth at the crossing. The slope length and steepness factor (LS) was estimated by using the length, width, and slope measurements in accordance with the LS equation in the USLE-Forest manual. The cover and support practices (CP) factor takes into account canopy cover, measured with a spherical densitometer, percent bare soil and time since tillage, and amount of onsite storage. Storage was examined visually for step effects, presence of invading vegetation, and type of ground cover. These four factors multiplied together generated an estimated erosion rate for each approach, which were weighted by area and both sides averaged to develop a potential erosion and sedimentation rate for each crossing. Several studies have compared erosion estimates of the USLE-Forest with direct erosion measures on roads and skid trails and concluded that the USLE provides reasonable quantifications of erosion and allows management option comparisons (e.g. Brown et al. 2013; Vinson et al. 2017a; Wade et al. 2012).

The Water Erosion Prediction Project (WEPP), developed by the USDA (Elliot et al. 1999), was used to estimate erosion for each crossing approach and compared to the USLE-Forest model values. Truck road approaches were described as “Forest/Road WEPP Management/Insloped-Road, unrutted” in the management file, and “Forest/Road WEPP Soils/(clay loam, silt loam, loam, sandy loam)” in the soils file based on Web Soil Survey soil textures (Brown et al. 2013; Vinson et al. 2017a; Wade et al. 2012). Climate files were created using the CLIGEN database from the nearest research station to each site. Hillslope files were created based on the road template data collected in the field. Rock content, bulk density, and vegetation types were not manipulated due to a lack of official field measurements for these parameters. Working files were left unmodified to best represent using the model as a management tool by someone in a nonacademic atmosphere. WEPP has also been used to estimate erosion from forest roads and comparison of model results have indicated that WEPP results can be more precise than the USLE if WEPP inputs are significantly varied or less satisfactory if standard WEPP inputs are used (Lang et al. 2017).

3.3.3 BMP Rating Justification

We used a rating system (BMP-, BMP-standard, BMP+) to categorize the implementation BMPs on roads and stream crossings (Figure 3.2). Stream crossing approaches that received a rating of BMP-standard showed evidence of pre-harvest planning based on the selection of crossing location, slope and soils, and crossing structures were correctly sized for watershed acreage and flow pattern (Table 3.1). Stream crossings with BMP-standard ratings had sufficient ground cover (mean 70%, range 35-99%) and presence of functioning water control structures that generally met the recommendations of the VDOF state BMP manual (mean 86%, range 30-100%). Crossings that received a BMP+ exceeded the recommendations of the manual by using additional ground cover, water control structures, and enhanced installation of crossing structures. BMP- ratings were used for crossings that did not implement the minimum recommendations of the BMP manual. Overall ratings were determined based on the summation of individual ratings of the four subcategories that address the presence and effectiveness of: 1) the road template, 2) water control structures, 3) crossing structures, and 4) ground cover.

Table 3.1. Criteria used to evaluate subcategories that determined overall BMP ratings at truck road stream crossings.

Subcategory within BMP-standard	Criteria based on the VDOF BMP Manual
Road Template	• Stable approaches • Stable cut and fill slopes • Appropriate ditches and cross drains • Follows natural contour • Road gradient between 2-10% • Evidence of pre-harvest planning
Water Control	• Appropriate spacing between water bars or diversions • Working structures that are not collapsed or filled • Drains to SMZ or vegetated area
Stream Crossing Structure	• Stable fill above culvert with riprap • Appropriate culvert and bridge lengths • Correct sizing of culvert based on watershed size • Culverts are not perched nor inhibit aquatic species migration • Fords have a hard rock bottom or appropriate geoweb reinforcement • Stable streambanks • Crossing installed at a right angle
Surface Cover	• Ground cover is applied immediately after harvest close-out • Barriers such as hay bales, silt fences, and check dams are used if necessary • Ground cover is well-distributed

Figure 3.2. Representative best management practice (BMP) ratings on stream crossing approaches for each region.

3.3.4 Data Analyses

All crossings that received a BMP- or BMP-standard crossing in the field were hypothetically upgraded either one or two times so that they could be considered BMP+ crossings. BMP- roads were first upgraded hypothetically to BMP-standard and next to BMP+, while BMP-standard roads received only BMP+ hypothetical upgrades. Potential BMP improvements were identified for each crossing approach so that we could evaluate potential erosion and potential costs of these upgrades. Based on a pilot study for our project (Nolan et al. 2015), the most common methods for reducing rates of erosion are reducing slope length by adding water control structures and adding cover to the approaches. In order to reflect these modifications in the USLE modelled erosion rates, we manipulated the LS and bare soil factors in the USLE-Forest equation. Both of these methods were successfully used to hypothetically reduce rates of erosion by Nolan et al. (2015). Adjusting the road template, which may be what is needed to theoretically improve the site, could cause pulsed releases of sediment to the stream and is beyond the scope of the study, therefore adjustment of the road template was not used as an alternative. By implementing water bars, geomorphic effects such as fill slope destabilization and fine sediment delivery could be prevented (Wemple and Jones 2003). Other improvements considered were the installation of a new culvert if the current one was undersized or collapsed, and the addition of geotextile or rock base to enhance a ford. However, there are no methods to reflect the sediment values associated with these improvements within the USLE. Stream crossing replacements have potential to increase erosion during installation (Taylor et al. 1999; Morris et al. 2016; Aust et al. 2011). Harris et al. (2008) found that structures replaced in California on sites with extensive erosion control methods recovered significantly within one rainy season.

Costs for additional water control structures, ground cover, and other closure expenses were estimated using the Virginia Tech Forest Road Costs Method (VTFRCM) modified by Conrad et al. (2012). While gravel is the most expensive ground cover option, it has been proven effective when adequately spread for a specific depth and distance (Swift 1986; Brown et al. 2015). Gravel was assumed to cost \$27.56/delivered tonne (\$25/ton); gravel costs were estimated by converting the density to mass by using the estimated volume required to cover the approach with a recommended depth of 7.62 centimeters (three inches) (Kochenderfer and Helvey 1987). Seed and mulch application costs were estimated based on costs per kilometer and subsequent conversion to \$ per square meter (Sawyers et al. 2012, Vinson et al. 2017b). A cost-benefit analysis was performed by dividing the cost of the improvement of a crossing by the change in erosion prediction between the current and hypothetical erosion rates, which produced a value in dollars per megagram ($/Mg) of sediment saved from entering the stream.

3.3.5 Statistical Analyses

JMP-Pro 13 was used to perform all statistical analyses at alpha level 0.05 (SAS Institute, Inc. 2016). As is common with operational research, data were not normally distributed, thus we analyzed data with a combination of descriptive statistics and nonparametric analysis, supplemented by regression. We determined means, medians, minimum, and maximum values for BMP levels within all regions and types of crossings, and we evaluated significant differences with nonparametric tests such as the Kruskal-Wallis test, followed by multiple comparisons using the Steel-Dwass all pairs test. We also used regression to interpret the potential relationships found between BMP implementation percentages and potential erosions rates.

3.4 Results and Discussion

The VDOF was notified for 5,039 harvests in 2016. We used our qualified data from the VDOF water quality specialists to estimate that approximately 1,537 harvest sites had stream crossings (30.5%). Of the harvests with crossings, an estimated 454 crossings were on truck roads (29.5%). We sampled 25 (16%) of 157 truck road crossings in the Mountains, 25 (11%) of the 224 truck road crossings in the Piedmont, and 25 (34%) of the 73 truck road crossings in the Coastal Plain.

Culverts were the most prevalent crossing type for truck roads in all regions; the Coastal Plain, Piedmont, and Mountain regions used culverts for 84%, 76%, and 64% of haul road crossings, respectively (Table 3.2). Culverts are advantageous for logging roads because they are simple to install, can carry heavy payloads without complex calculations of weight limits, and can be either temporary or permanent (Morris et al. 2016). Disadvantages of culverts include placement of fill dirt in the stream channel with associated sedimentation, the tendency to use culverts smaller than recommended for water yields, increased downstream water velocity and scouring, restriction of stream aquatics, and problems associated with culverts becoming clogged (Warrington et al. 2017). Portable bridges are commonly recommended for stream crossings because they can cause less stream disturbance, can be cost effective when used repeatedly, and do not clog as readily as culverts. However, portable bridges are often designed for skidder use and may not be weight compatible for log trucks. Also, portable bridges are more expensive than culverts when used in a permanent crossing application. Portable bridges were used only in the Mountains and Piedmont regions on temporary truck roads. Our sample found no haul road stream crossings in the coastal plain region that used portable bridges. Fords are considered the least expensive stream crossing and can carry heavy loads if the ford has a hard rock bottom or if reinforced with geotextile and stone. Fords can also carry large volumes of water and debris without becoming blocked. However, fords tend to allow increased stream sedimentation due to the repeated churning of stream sediments, and their use is limited by appropriate weather conditions (Morris et al. 2016). We found that fords were used between 12% to 28% for haul road crossings across all regions.

We inspected the area downstream of the stream crossings in a manner similar to the Virginia Department of Forestry BMP inspections. Our visual inspections of sediment pathways, SMZ breakthroughs, and unstable crossing structures were evidence of recent sedimentation in stream channels below 28.6% of culverts, 28.6% of unimproved fords, 25% of portable bridges, 14.3% of improved fords, and 0% of permanent bridges. Our results are supported by the findings of Morris et al. (2016) that evaluated stream crossings and sediment in the Piedmont region. Their results concluded that permanent bridges produced less sediment than reinforced fords and that culverts produced more stream sediments, even when BMP+ level BMPs were applied. Aust et al. (2011) examined 23 stream crossings in the Piedmont and concluded that bridges tended to produce the least sediment, culverts produced the most sediment, and reinforced fords were intermediate, however they also emphasized that the approach conditions were often more important to sediment delivery rather than crossing structure. We suspect that our temporary bridges produced similar sediment to culverts because of the erosion generated by poor support on the banks or sediment generated by removal. Wear et al. (2013) found that approach closure BMPs are critical for reduction of sediment following removal of temporary crossings in the Piedmont.

Table 3.2. Number and percentage of crossing types by region on truck road stream crossings.

	Crossing Type	% Crossing Type
Mountains	25	
culvert	16	64.0%
unimproved ford	4	16.0%
improved ford	3	12.0%
portable bridge	2	8.0%
Piedmont	25	
culvert	19	76.0%
unimproved ford	1	4.0%
improved ford	2	8.0%
portable bridge	2	8.0%
permanent bridge	1	4.0%
Coastal Plain	25	
culvert	21	84.0%
unimproved ford	2	8.0%
improved ford	2	8.0%
All Crossings and Regions	**75**	100%

The overall BMP audit score for stream crossings on truck roads was 82%. The audit question (question 13) regarding the presence and adequate implementation of water control structures on approaches scored the lowest “yes” percentage across crossing types (Table 3.3).

Culverts (69.1%), fords (50%), and bridges (50%) on truck roads all had the lowest score for this water control structure question. This result is potentially explained by the common practice of continuing to use permanent truck roads so that such roads are never fully closed out after harvest. Therefore these permanent truck roads are subject to low-volume traffic that damages water diversion structures. We also found that fords tended to lack gravel and only had 50 feet of clean gravel 57% of the time (question 15). All other questions for truck roads regarding crossing type scored ≥ 71%. Because of the prevalence of culverts on truck roads, it is important to address the most common issues with their usage, evident in questions 2-6 and 12 in the VDOF BMP audit (Table 3.3, Table 3.4, Figure 3.3). Many culverts sampled were undersized according to watershed size and stream flow pattern; this is usually the case to reduce costs, although often maintenance is required to manage smaller culverts (Gillespie et al. 2014; O'Shaughnessy et al. 2016).

Regionally, the Mountains had the lowest BMP implementation score for proper water diversion structures (54%), followed by Coastal Plain (65%) and Piedmont (76%) (question 13). We suspect multiples reasons for regional differences. For example, it can be difficult to maneuver equipment on steeper terrain and transport soil with rocky parent materials in the Mountains region. To stabilize streambanks and culvert crossings, fill dirt is recommended to be at a depth at least one-half of the culvert diameter and/or 12 inches. The Mountains (60%) and Piedmont (68%) didn’t use enough fill material to cover culverts (question 4), while the Coastal Plain (63%) had more issues regarding channel undercutting and proper installation (question 2). When ground cover and streambank vegetation is removed and overland flow occurs, stream flow volumes increase, causing sediment transport and streambank failure. Improper culvert installation can cause channel undercutting and streambed scouring (Georgia Soil and Water Conservation Commission 2000).

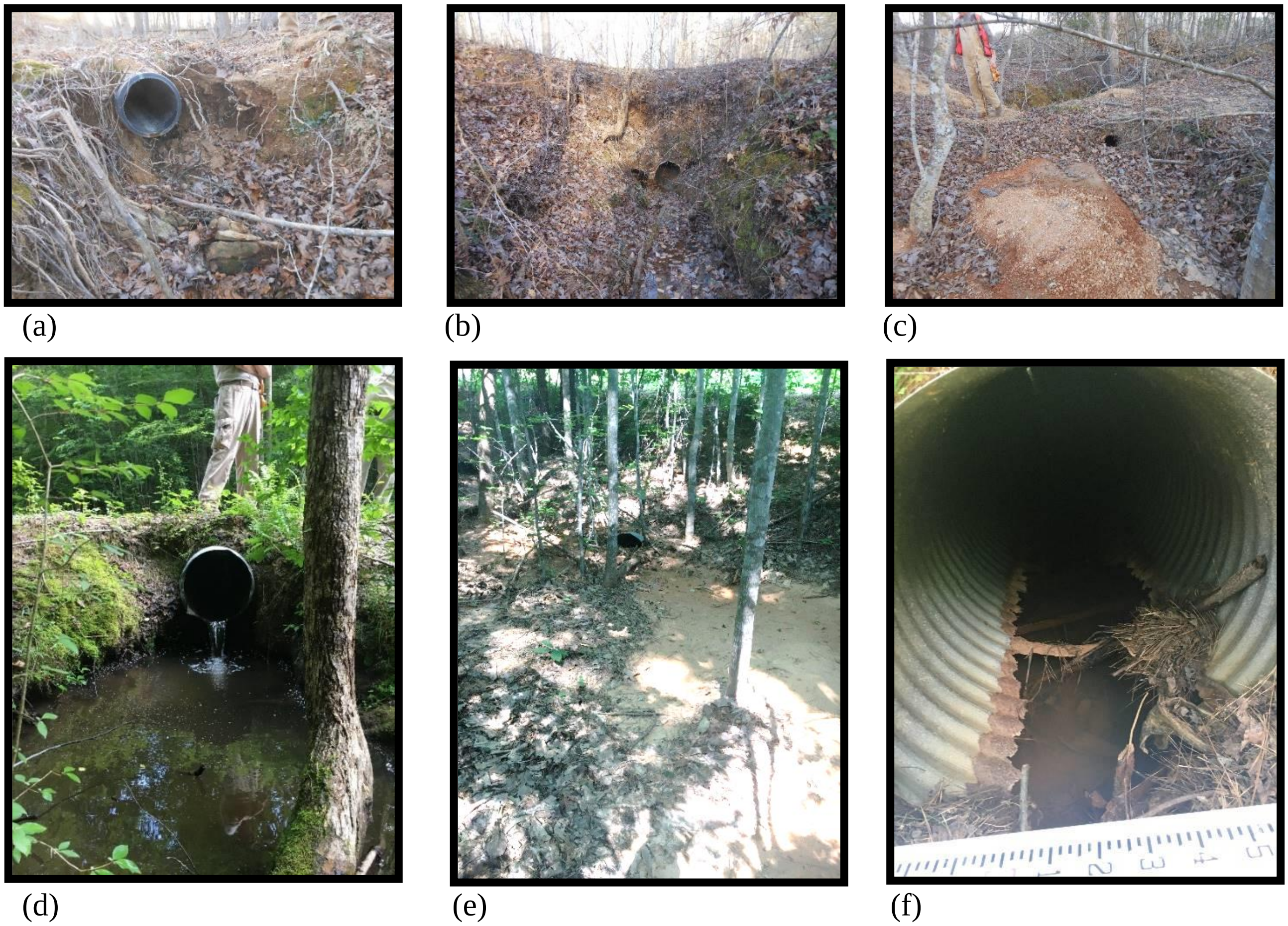
Table 3.3. VDOF BMP Audit questions regarding stream crossings; **bolded** questions are most relevant and potentially correlate with erosion on approaches.

Questions regarding stream crossings from VDOF Questionnaire	Mountains		Piedmont		Coastal Plain	
	N	Yes (%)	N	Yes (%)	N	Yes (%)
1. Are approaches stable and unlikely to contribute sediment to the stream?	25	92.0	25	76.0	25	88.0
2. Are culvert pipes installed properly in the channel to avoid undercutting and channel erosion?	15	93.3	19	78.9	20	65.0
3. Are culverts and bridges of adequate length?	17	82.4	21	71.4	20	90.0
4. Are culverts covered with adequate and appropriate fill material?	15	60.0	19	68.4	18	83.3
5. Are culverts covered with gravel to reduce erosion near the stream? (crossing)	15	86.7	19	73.7	19	73.7
6. Are culverts properly sized according the BMP manual Table 6 and 7 or Talbots formula?	15	73.3	19	73.7	20	70.0
7. Are fords used only where a natural rock base (or geoweb) and gentle approaches allow?	7	100.0	3	66.7	4	100.0
8. Are headwalls stabilized with vegetation, rock, or fabric to minimize cutting?	16	93.8	18	88.9	12	75.0
9. Are permanent bridge abutments adequate and stable?	-	N/A	1	100.0	-	N/A

10. Are stream banks and approaches reclaimed with sufficient vegetation, rock or slash?	25	92.0	25	84.0	25	84.0
11. Are stream crossings installed at or near right angles where possible?	25	100.0	25	100.0	25	100.0
12. Are temporary culverts, pole bridges, and bridges removed?	4	100.0	2	100.0	4	75.0
13. Are water diversion structures present where needed on approaches?	24	54.2	25	76.0	23	65.2
14. Do all ford crossings avoid restricting the natural flow of water?	7	100.0	3	100.0	4	100.0
15. Do all ford approaches have a 50-foot approach of clean gravel?	7	85.7	3	0.0	4	50.0
16. Do all ford crossings have underlying geo-textiles where needed on approaches?	-	N/A	2	0.0	-	N/A
17. Is the addition of unnatural materials in the stream to facilitate the use of a ford minimized?	7	100.0	3	100.0	4	100.0
18. Were pole bridges used only in appropriate circumstances?	-	N/A	-	N/A	-	N/A

Table 3.4. Distribution of BMP Audit answers by crossing structure (refer to Table 3.3 for question number).

Audit Question	**Culverts**		**Fords**		**Portable Bridges**	
	N	Yes (%)	N	Yes (%)	N	Yes (%)
Q1	56	82.1	14	92.9	4	100.0
Q2	54	77.8	-	N/A	-	N/A
Q3	54	79.6	-	N/A	3	100.0
Q4	52	71.2	-	N/A	-	N/A
Q5	53	77.4	-	N/A	-	N/A
Q6	54	72.2	-	N/A	-	N/A
Q7	-	N/A	14	92.9	-	N/A
Q8	38	84.2	5	100.0	2	100.0
Q9	1	100.0	-	N/A	-	N/A
Q10	56	85.7	14	85.7	4	100.0
Q11	56	100.0	14	100.0	4	100.0
Q12	6	83.3	-	N/A	4	100.0
Q13	55	69.1	12	50.0	4	50.0
Q14	-	N/A	14	100.0	-	N/A
Q15	-	N/A	14	57.1	-	N/A
Q16	-	N/A	2	0.0	-	N/A
Q17	-	N/A	14	100.0	-	N/A
Q18	-	N/A	-	N/A	-	N/A



(a) (b) (c)

(d) (e) (f)

Figure 3.3. Examples of poorly managed culverts that are (a) washed out, (b) collapsed, (c) undersized, (d) perched, (e) clogged, or (f) corroded.

There were no significant differences among regions for the BMP audit scores (p = 0.6636) (Table 3.5). However, there are significant differences between audit scores in the BMP- category and BMP-standard category for the Piedmont (p=0.0017) and Coastal Plain (p = 0.0278), but differences between BMP-standard and BMP+ were not significant. The Mountain region had no significant differences between BMP- and BMP-standard audit scores, but did present one significant difference between BMP-standard and BMP+ scores (p=0.0102). Importantly, both BMP scores and cost-benefit ratios followed the trend and distribution by region. The Coastal Plain and Piedmont have an insignificant difference between BMP-standard and BMP+ levels ($/Mg), but the Mountain region has a substantial increase in costs to reduce one Megagram of sediment moving from a BMP-standard to a BMP+ (Table 3.9).

Table 3.5. Summary statistics for stream crossing audit score by region and BMP rating. Values not followed by the same letter within a column specific to a region are significantly different using the Steel-Dwass All Pairs test at α = 0.05.

Region		**N**	**Mean**	**Median**	**SD**	**Min.**	**Max.**
Mountains	BMP-	2	70	70ab	28.3	50	90
	BMP_std	15	82.5	85.7a	16.2	30	100
	BMP+	8	97.2	100b	5.1	88	100
Piedmont	BMP-	6	38.0	33a	19.1	20	66.7
	BMP_std	16	90.8	95b	12.6	60	100
	BMP+	3	100	100ab	0	100	100
Coastal Plain	BMP-	5	57.4	60a	12.4	40	70
	BMP_std	17	83.6	88.9b	16.5	50	100
	BMP+	3	100	100ab	0	100	100

There were no significant differences in erosion rates by region in the results of either model (USLE p=0.2114; WEPP p=0.2201) (Table 3.6). Both the USLE and WEPP models were designed to estimate erosion from agricultural lands and have been modified since development to encompass other land uses, including forested watershed and forest harvesting conditions. The USLE is most widely used in the forestry community and worldwide (Liu et al. 2000). WEPP performs poorer than USLE unless interior files are heavily amended (Vinson et al. 2017a). Both models tend to overestimate erosion rates as they increase beyond 11.2 Mg/ha/yr (Lang et al. 2017). Erosion rates ranged from zero megagrams/hectare/year to 49.2 megagrams/hectare/year using USLE, and ranged from 3.4 to 73.6 megagrams/hectare/year using WEPP. The USLE values were used to portray the significant relationship with audit scores and perform hypothetical upgrades; erosion rates decreased as BMP implementation increased (Figure 3.4; Table 3.9). For a more accurate prediction of erosion rate by audit score, we adjusted the audit scores by only including questions pertaining to erosion on approaches, which are the questions bolded in Table 3.3 (Table 3.3; Figure 3.4).

Table 3.6. Erosion rates and audit score summary statistics by region. Values not followed by the same letter within a column are significantly different using the Steel-Dwass All Pairs test at α = 0.05.

	Mean	**Median**	**SD**	**Min.**	**Max.**
Audit Score					
Mountains	86.2	88.9a	16.3	30	100
Piedmont	79.2	90a	27.2	20	100
Coastal Plain	80.3	87.5a	19.3	40	100
Erosion Rate (Mg/ha/yr) USLE					
Mountains	8.7	2.3a	12.6	0.0	49.2
Piedmont	9.6	5.7a	10.0	0.1	40.1
Coastal Plain	5.4	3.6a	4.1	0.1	13.0
Erosion Rate (Mg/ha/yr) WEPP					
Mountains	17.5	12.4a	17.2	3.4	73.6
Piedmont	19.9	16.7a	12.5	4.4	45.1
Coastal Plain	15.6	10.1a	13.1	7.2	58.4

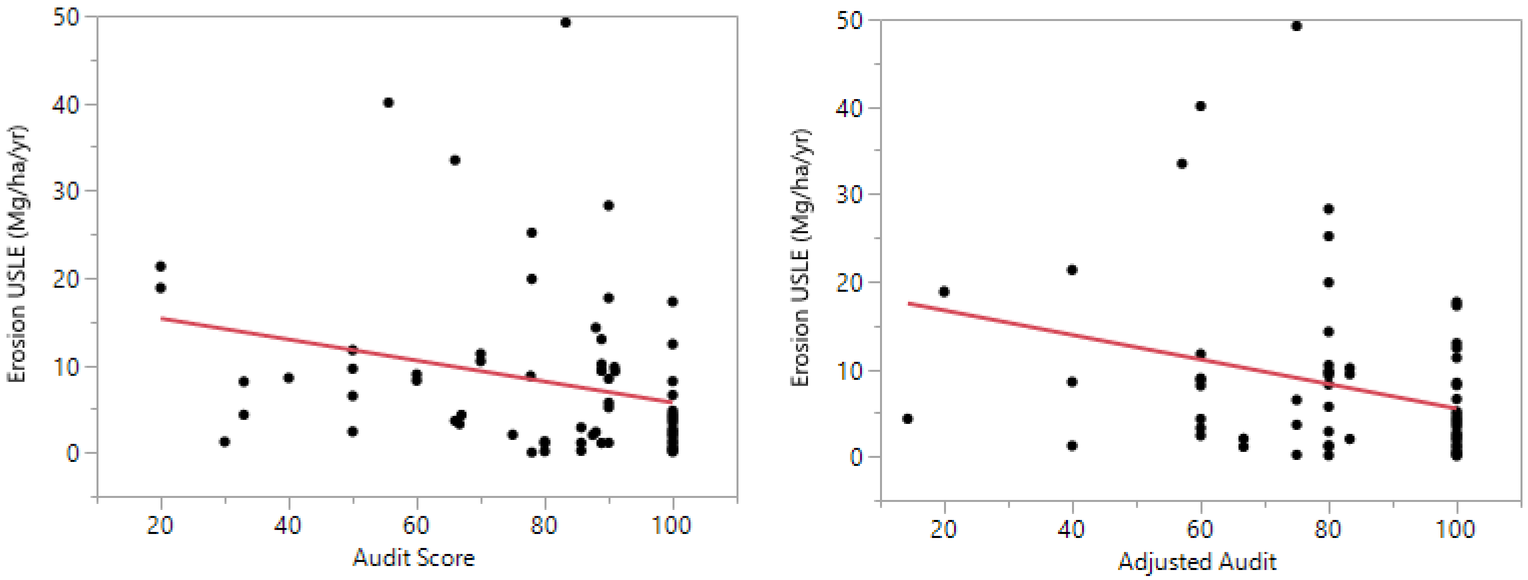


Figure 3.4. Linear regression portraying negative correlation between audit scores and erosion rates (Left: r^2 = .07165, p = 0.0202), (Right: r^2 = .08623, p = 0.0106).

At least 30% of crossings in all regions lacked working water control on stream crossing approaches (Table 3.7a). In the Coastal Plain and Piedmont, water turnouts were the primary form of drainage. These structures are simple to implement and cost approximately $25 to install

(Conrad et al. 2012). They are common on permanent truck roads that accommodate regular traffic, where water bars are not applicable. Water bars were also used substantially on temporary roads. In the Mountains, water bars and broadbased dips were used most often. Seventy-two percent of BMP- crossings did not have water control structures. Approaches that received BMP+ ratings used broadbased dips, water bars, and/or water turnouts (Table 3.7b).

Gravel was the most common (≥56%) cover type for haul roads within all regions (Table 3.8a). Grass was the second most commonly used cover type. Gravel was present most often on approaches regardless of BMP rating, and it is necessary to note this index does not specifically quantify if the cover application is satisfactory. Sixty-eight percent of BMP- approaches used gravel, but it was most likely not spread consistently and/or did not reach the recommended depth that ensures effectiveness. Grass was used about 15% of the time in across all BMP rating categories (Table 3.8b). The BMP manual recommends establishing ground cover immediately following harvest operations to protect the soil from raindrop splash and formation of rills.

Table 3.7a. Distribution of water control structures by region (based on 144 truck road approaches).

	Broadbased dip	Cross drain	Slash dam	Rolling dip	Sediment pool	Silt fence	Water bar	Water turnout	None
Mountains	14.6%	0.0%	0.0%	2.1%	2.1%	2.1%	14.6%	12.5%	52.1%
Piedmont	7.1%	1.8%	1.8%	5.4%	8.9%	0.0%	17.9%	26.8%	30.4%
Coastal Plain	13.7%	2.0%	0.0%	2.0%	0.0%	0.0%	21.6%	23.5%	37.3%

Table 3.7b. Distribution of water control structures by BMP rating for drainage sub-category (based on 144 truck road approaches).

	Broadbased dip	Cross drain	Slash dam	Rolling dip	Sediment pool	Silt fence	Water bar	Water turnout	None
BMP-	0.0%	0.0%	0.0%	0.0%	5.6%	0.0%	2.8%	19.4%	72.2%
BMP-standard	14.0%	1.8%	90.0 %	4.4%	3.5%	90.0%	22.8%	21.1%	30.7%
BMP+	40.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	40.0%	0.0%

Table 3.8a. Distribution of cover types by region.

	Chips	Grass	Gravel	Local stone	Mulch	Natural veg or rock	Seed and mulch	Slash	Wooden mats	None
Mountains	3.8%	18.9%	58.5%	3.8%	3.8%	0.0%	5.7%	1.9%	0.0%	3.8%
Piedmont	0.0%	21.9%	56.3%	0.0%	3.1%	6.3%	7.8%	3.1%	1.6%	0.0%
Coastal Plain	3.6%	9.1%	61.8%	0.0%	14.5%	0.0%	9.1%	0.0%	0.0%	1.8%

Table 3.8b. Distribution of cover types by BMP rating for ground cover sub-category.

	Chips	Grass	Gravel	Local stone	Mulch	Natural veg or rock	Seed and mulch	Slash	Wooden mats	None
BMP-	0.0%	12.0%	68.0%	0.0%	8.0%	4.0%	0.0%	0.0%	0.0%	8.0%
BMP-standard	3.0%	15.2%	54.5%	1.5%	9.1%	4.5%	7.6%	3.0%	0.0%	1.5%
BMP+	2.5%	19.8%	59.3%	1.2%	4.9%	0.0%	9.9%	1.2%	1.2%	0.0%

Potential costs to implement BMP enhancements ranged from \$18.75-\$423.01, with an average price of \$151.65 to upgrade from BMP- to a BMP-standard. Costs to upgrade a BMP-standard to a BMP+ range from \$18.75-\$400, with an average of \$114.05. It is important to note that there were no significant differences among regions in costs per crossing ($p = 0.0878$), nor was there a substantial difference in average costs for the upgraded categories. The results indicate that BMPs on truck roads can be applied at the recommended BMP level (BMP-standard) for a reasonable cost, and can be upgraded once more to a BMP+ level by spending approximately twice as much. BMP+ implementations may be hampered in the Mountain region in Virginia, where steep terrain and rockier parent materials may make BMP+ implementations more expensive (question 13, Table 3.2).

We also considered percent increase in costs to move from a BMP-standard to BMP+, using the 13 BMP- truck road crossings in the sample, and calculated percent change in erosion rates to estimate increase in benefits for each rating. The Mountain region has a 73.2% increase in costs, but a 59.2% increase in benefits. The Piedmont region would experience a higher cost increase at 142% to reach a BMP+ rating, while increasing benefits by 77.5%. The Coastal Plain benefits outweighed the cost increase by 5.7% (Table 3.9). Overall, the average increase in benefits is 66.1%, with a 102% increase in costs. Depending on the terrain, sensitive ecological areas, and previous water quality issues, it may be worth installing exceptional grade BMPs; in most situations, correctly implemented standard BMPs will effectively control erosion and eliminate unwanted expenses.

Table 3.9. Average potential erosion rates and costs before and after hypothetical upgrades were made to truck road crossings.

	N	Average before upgrade (Mg/year)	Average after upgrade (Mg/year)	Percent increase in benefits	Average upgrade cost ($/crossing)	Percent increase in costs	Average upgrade cost/benefit Ratio ($/Mg)
Mountains							
BMP-	2	0.40	0.13	72.9%	181.10	100%	5585.10
BMP_std	15	0.28	0.06	59.2%	101.67	73.2%	1149658.81
Piedmont							
BMP-	6	0.76	0.42	45.5%	128.18	100%	1197.40
BMP_std	16	0.35	0.07	77.5%	105.55	142%	1315.12
Coastal Plain							
BMP-	5	0.29	0.17	36.5%	168.04	100%	2242.05
BMP_std	17	0.14	0.02	72.0%	132.12	66.3%	5080.74
BMP-	13	0.52	0.28	46.2%	151.65	100%	2274.20
BMP-std	61	0.25	0.05	70.4%	114.05	102%	322703.42

3.5 Conclusions and Recommendations

Virginia has approximately 5,039 harvests per year and 232,300 acres harvested in 2016 (VDOF 2016b). We extrapolated our sample and results to statewide audit scores and erosion rates using weighted averages. Based on our extrapolation there are approximately 82 truck road crossings that would be classified as BMP- each year, with an average audit score of 46.6%, contributing 14.5 Mg/ha to the annual erosion rate; 287 crossings classified as BMP-standard, with an average audit score of 86.8%, accounting for 8.3 Mg/ha of the annual erosion rate; and

86 BMP+ crossings, with an average audit score of 98.4%, producing 4.0 Mg/ha/yr of erosion. Best management practices are practical techniques that allow sustainable harvest, protect forest resources such as water for multiple uses, and maintain economic growth in the wood products industry. Some major conclusions from this study include:

1. Virginia has good BMP implementation scores for haul road stream crossings; 83% of truck road crossings sampled in this study were categorized as BMP-standard or BMP+, which had an average audit score of 88%.
2. Truck road stream crossings can be extremely sensitive after harvest operations are complete. In nonindustrial harvests, roads were prone to moderate traffic by private landowners even after the roads were retired. On larger industrial tracts, roads maintenance was more obvious, however access roads to various stands of timber were not formally closed. Permanent activities could potentially lead to higher rates of soil erosion and compaction during high intensity rainfall events, but they do prevent the construction of new roads.
3. Upgrading BMPs from the BMP- level is a relatively small cost to loggers and landowners, especially when BMPs are integrated throughout the duration of the harvest. While we were expecting an exponential relationship between costs of increased BMP enhancements and erosion rates that would eventually prove diminishing returns, truck roads in this study showed a more linear trend as each BMP level was met with more rigorous implementation and an average reduction of 5 Mg/ha/yr of erosion for each upgraded level.
4. Gravel, the most commonly used surfacing material for forest truck roads at stream crossing approaches in all regions of Virginia, has been shown to reduce sediment

production rates from native surface forest roads by 12-25 times (Coe 2006). We found that approximately 60% of stream crossing had been graveled and suggest that gravel applications could be used to improve conditions at most permanent stream crossings.

5. When properly installed, water turnouts and broadbased dips were found to be the most effective drainage structures for permanent roads. Temporary roads should be closed out with water bars and slash, if available, to deter unpermitted traffic.
6. As BMP implementation rates increased, modelled erosion rates decreased. This correlation contributes to previous findings that BMPs are effective at controlling erosion at stream crossings.

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4.0 ESTIMATED COSTS AND EROSION CONTROL OF DIFFERENT LEVELS OF FORESTRY BEST MANAGEMENT PRACTICES IMPLEMENTED AT 154 OPERATIONAL STREAM CROSSINGS IN VIRGINIA, USA

4.1 Abstract

Operational stream crossings on forest roads and skid trails are potential sediment delivery areas from timber harvests that can negatively affect water quality if sufficient and appropriate best management practices (BMPs) are not implemented. Virginia has three major physiographic regions (Mountains, Piedmont, Coastal Plain), and each require some specificity regarding BMP guidelines for water quality protection. Furthermore, truck roads and skid trails utilize somewhat different drainage and erosion control BMPs to maintain sufficient working conditions and access to timber. Also, implementation levels inherently differ and thus offer varying benefits and associated costs. Therefore, to examine BMP implementation and costs across different regions and road types, we evaluated BMPs installed on 25 truck road and 25 skid trail stream crossings from each physiographic region (3 regions x 2 road types x 25 samples = 150 stream crossings). We modelled erosion rates using WEPP:Road and USLE-Forest to achieve erosion estimates at different levels of BMP implementation. We also examined the effects of road type, crossing structure, soil texture, cover percentages, and region on modelled erosion rates and costs. Cost-benefit ratios were developed to depict dollars spent on improving BMPs per megagram of erosion prevented by hypothetically upgrading stream crossings to over 95% BMP implementation. Results indicate that potential erosion rates decreased with increasing BMP implementation ($p < 0.0001$). Average audit scores for stream crossings were 88% on skid trails and 82% on truck roads. To upgrade from a BMP- to BMP-standard, the cost-benefit ratio averaged \$166.62/Mg for skid trails and \$2274.22/Mg for truck

roads. Enhancement from BMP-standard to BMP+ level is less economically efficient and BMP implementation efficacy at stream crossings appears to plateau at the BMP-standard level.

4.2 Introduction

It is widely acknowledged that forest operations involving roads and skid trails can create bare soil areas that result in soil erosion (Wynn et al. 2000; Shepard 2006; Anderson and Lockaby 2011; Aust and Blinn 2004; Cristan et al. 2016). In the southeastern U.S., forestry is often practiced on severely eroded and abandoned agricultural lands or lands that were too wet, steep, or rocky to be suitable for agriculture. The Piedmont region epitomizes such “old field” forestlands. Between 1810 and 1930, an estimated 10-30 cm of topsoil was lost from the southeastern upland Piedmont and some of this eroded material is still stored in streambeds (Trimble 1974; Jackson et al. 2005). As a result, current forestland in the region may have lower nutrient and organic contents, presence of erosion gullies, and aggraded streams. Such previously eroded lands are sensitive areas for erosion, with 90% of soil loss originating from bare soil areas such as forest truck roads and skid trails (Hoover 1952; Yoho 1980). The history of agricultural erosion highlights the need for erosion control measures on the current forestlands located on such erosion prone sites.

Sediment derived from silvicultural activities is categorized as nonpoint source pollution and this classification exempts the majority of forest operations from the National Pollutant Discharge Elimination System (Boston 2012). Stream crossings that are not properly constructed and maintained can lead to sedimentation that harms water quality and downstream aquatic species by decreasing dissolved oxygen concentrations, increasing turbidity, and altering geomorphology (Neary et al. 1989; Williams et al. 1999; Warrington et al. 2017). Stream crossing approaches can also initiate soil erosion if BMPs are not implemented, leading to impaired water quality (Aust et al. 2011).

Forestry BMPs are based on a combination of operational techniques developed through operational experience and applied research (Shepard 2006; Aust and Blinn 2004; Edwards and Williard 2010; Cristan et al. 2016). All southeastern states developed forestry BMPs for the protection of water quality and Virginia's BMPs are typical for the region with a variety of operational recommendations including roads, skid trails, stream crossings (Aust 1994). The Virginia Department of Forestry (VDOF) developed best management practices that will either minimize erosion or trap eroded material before it reaches a water body, thereby protecting water quality with a secondary benefit of maintaining site productivity (VDOF 2011). Virginia BMPs are quasi-regulatory and monitored by the Virginia Department of Forestry, which has authority to impose fines for violations of the Virginia Silvicultural Water Quality Law. Stream crossings are of particular interest due to their proximity to the stream, leading to numerous studies examining erosion control and water diversion onto forest floor prior to reaching the stream (Croke and Mockler 2001; Croke et al. 2006). Streamside management zones (SMZs) are maintained in order to trap eroded sediment and SMZs can trap 70-99% of sediment, stabilize stream banks, filter overland flow, and provide habitat complexity from downed woody debris, making SMZs an essential BMP to maintain water quality (Jackson and Kolka 2002). SMZs are a widely utilized and effective method for filtering nutrients and trapping sediment prior to stream entry (Rivenbark and Jackson 2004; Lakel et al. 2010; Lang et al. 2015).

Erosion from forest operations can differ due to site conditions including geology, topography, climate, and soil properties; however, BMPs that are properly implemented are sufficient for controlling erosion based on the finding of numerous studies (Aust and Blinn 2004;

Cristan et al. 2016). During active harvest operations, erosion from skid trails may be more significant than that from road surfaces due to lower trail construction standards such as steeper slopes and a lack of surfacing. However truck roads can deliver sediment to streams due to higher hydrologic connectivity (Sidle et al. 2004), greater contributing area per crossing, and permanency of the road (Lang et al. 2017). With increased connectivity, streams can aggrade over time due to a sediment supply that exceeds the transport capacity of the channel (Jackson and Pringle 2010).

Expenses associated with BMP implementation have not been well documented due to the complexity of individual circumstances and operating practices of loggers and landowners, including equipment ownership, state implementation standards, and regional soil and terrain circumstances (Montgomery et al. 2005). BMPs are commonly installed by the logging contractors, but implementation costs are also dispersed to landowners in the form of lower stumpage values and to the manufacturing facilities in the form of increased raw material costs. Costs associated with BMP implementation include materials, machinery, and labor required, as well as the loss in operational productivity due to time spent constructing structures such as water bars and turnouts and applying ground cover (Kilgore and Blinn 2003; Montgomery et al. 2005). For example, a recent study in the northeastern U.S. estimated BMP implementation costs to range from $0-62/acre, and cause a 0-20% loss in productivity (Kelly et al. 2017). Loggers can reduce material and machine costs and labor hours by planning access during the preharvest planning phase. Adequate preharvest planning can allow access to timber with minimum numbers of stream crossings (Aust et al. 1996; Shaffer and Meade 1997; Wynn et al. 2000; VDOF 2011). Agencies struggle with identifying the ideal level of BMP implementation which will provide acceptable levels of water quality protection without making BMP expenses cost prohibitive. Several evaluations of the costs and benefits of increasing BMP implementation have concluded that benefits reach a plateau and stabilize while the costs continue to escalate (Aust et al. 1996; Cubbage 2004; Wear et al. 2013; Nolan et al. 2015).

BMPs are implemented based on site and operational specifics and guidelines are adjusted accordingly as operations change and research provides new insights (Cristan et al. 2018). Currently, certification programs such as American Tree Farm, Sustainable Forestry Initiative (SFI), and the Forest Stewardship Council (FSC) all emphasize the appropriate implementation of BMPs on lands accredited by their programs. The ecological sustainability, economic success and societal acceptance of forest operations depend on stewardship practices such as the implementation of best management practices by loggers as they harvest timber. Potential degradation to natural resources, the national success of best management practices, as well as recent litigation (NEDC v. Brown 2011), have emphasized the need for studies regarding the implementation, effectiveness, and costs of BMPs.

4.2.1 Objectives

A review of the literature supports the premise that BMPs provide important protective measures for water quality at stream crossings. The literature also indicates that such BMPs have associated costs. However, the literature provides less insight into the effects and costs of implementing different levels of BMPs at stream crossings across a range of sites. Thus, our study was designed to quantify the effectiveness and costs of best management practices implemented at stream crossings on truck roads and skid trails across a range of physiographic conditions. We elected to use Virginia due to proximity for researchers, but the physiographic regions and operations are representative for sites across the southeastern United States. We estimated erosion using on-site data combined with empirical modelling; estimated costs by documenting operation used combined with existing cost models; and conducted simple cost-benefit analyses by comparing the erosion prevented compared to the estimated costs of applying BMPs. Previous literature clearly indicates that BMPs are sufficient to control erosion when applied correctly. To better understand implementation techniques and site-specific challenges of BMPs, this study characterizes similarities and differences between truck road and skid trail BMPs, as well as regional comparisons within Virginia regarding BMPs, costs, and erosion rates. This manuscript's specific objectives are to:

1. Summarize the characteristics of stream crossings in each physiographic region of Virginia,
2. Establish an overall cost-benefit ratio for truck road crossings and skid trails and determine the average amount of erosion reduced when BMPs are improved for each road type,
3. Compare truck road and skid trail BMP implementation and erosion rates,
4. Define shared and specific BMP inadequacies for each road type, and
5. Discuss the Virginia Department of Forestry BMP manual guidelines with respect to the study results.

4.3 Methods

4.3.1 Site Selection

We evaluated 154 stream crossings for BMP implementation and erosion processes on harvests completed in 2016 (Figure 4.1). Recent harvest sites were suggested by VDOF water quality specialists to ensure that selected sites actually had stream crossings. Included sites were required to be those with silvicultural harvest operations, rather than land use conversions, and included harvests were greater than 20 acres. Landowners were contacted for permission to access harvest sites. We evaluated stream crossing approaches for BMP implementation using portions of the VDOF BMP audit and modelled erosion rates using the Universal Soil Loss Equation modified for forestland (USLE-Forest) (Dissmeyer and Foster 1984) and the Water Erosion Prediction Project modified for roads (WEPP-Roads) (Elliot 1999). We recorded stream characteristics using Rosgen stream classification techniques (Rosgen 1994). We evaluated 79 skidder crossings and 75 truck road crossings (51 Mountains, 50 Piedmont, 53 Coastal Plain).

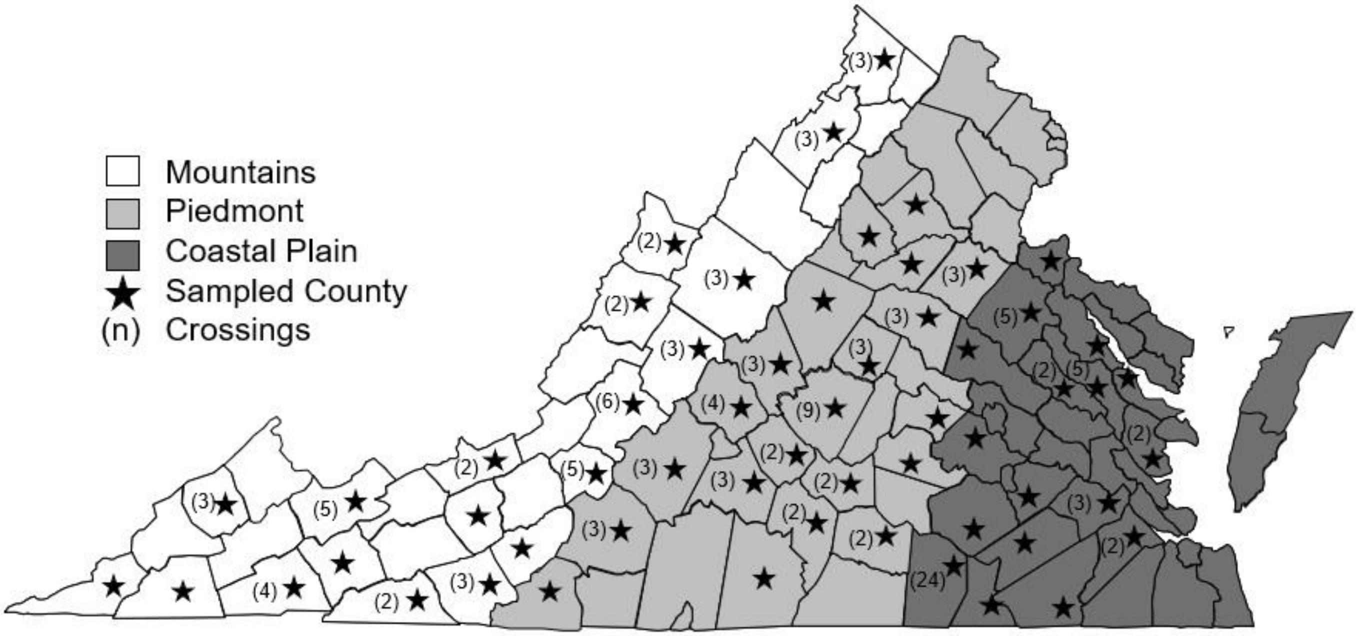

Figure 4.1. Sampled counties for truck road and skid trail stream crossings by physiographic region of Virginia.

4.3.2 Stream Crossing Site Measurements

Stream crossing approach lengths and widths were measured with a 100-ft tape, road and trail gradients were measured to the nearest 1% with a clinometer, and streambed slopes were determined with differential leveling using a clinometer and Philadelphia rod. For comparison to BMP manual recommendations, stream crossing structure characteristics were recorded including: bridge and culvert lengths, culvert diameters, and heights above streambeds. Water control structures and erosion control techniques were evaluated for effectiveness by determining ground cover percentages and visually observing sediment breakthroughs and deposition into the stream. Ground cover was determined by walking a patterned transect along the approach and counting footsteps where the toe of the boot landed on covered ground and bare ground (count of covered steps/total steps x 100= % ground cover). Streambed slope and characteristics were measured according to Rosgen's classification system. Six to eight pictures of the approaches and stream were taken and a GPS location was recorded to complement further analyses in the office.

4.3.3 Erosion Models

The USLE-Forest *(A=K x R x LS x CP)* accounts for site specific variables like rainfall erosivity and precipitation patterns within the R factor of the erosion equation. The K factor represents soil erodibility based on soil textures and Web Soil Survey classifications. The LS factor reflects road gradient and length of the approach and was determined by using the internal LS equation. The cover and practices factor (CP) encompasses site conditions regarding bare soil/ground cover, canopy cover, onsite storage, and time since tillage. These conditions are based on ground cover percentage, step formation percentage, and presence of invading vegetation and fine roots. The factors multiplied together generates an estimated erosion rate in megagrams/hectare/year (A).

The WEPP model can also generate an erosion rate and considers similar site characteristics as the USLE, such as soil texture, climate, hillslope and road template, and management factors. Minimal changes were made to the model for this study and climate files were appropriately used based on the nearest CLIGEN database station. Rock content, vegetation, and soil bulk density were not included in modelling due to lack of data collected in the field for these parameters. Truck road approaches were described as “Forest/Road WEPP Management/Insloped-Road, unrutted” in the management file, and “Forest/Road WEPP Soils/(clay loam, silt loam, loam, sandy loam)” in the soils file based on Web Soil Survey soil textures. Skid trail approaches were described as “Forest Bladed Road” in the management file, and “Disturbed Skid (clay loam, silt loam, loam, sandy loam)” in the soils file based on Web Soil Survey soil textures.

4.3.4 BMP Rating Development

A rating system was developed to classify BMP implementation at stream crossings into categories that reflected the fulfillment of Virginia BMP manual requirements (Figure 4.2). Crossing approaches received four subratings for: 1) road template, 2) ground cover, 3) drainage, and 4) crossing structure, and then received an overall BMP rating (BMP-, BMP-standard, BMP+) based on the majority of the subrating scores (Nolan et al. 2015; Morris et al. 2016). BMP-standard crossings complied with the BMP manual by using appropriate water control structures, sufficient ground cover, properly sized crossing structures, and evidence of pre-harvest planning with regard to road location, template, and slope (Table 4.1). BMP+ crossings exceeded the manual expectations and had enhanced implementation within some or all of the subcategories. BMP- ratings did not meet the minimum recommendations of the manual. These ratings along with erosion estimates allowed us to characterize relationships between predicted erosion and BMP implementation.

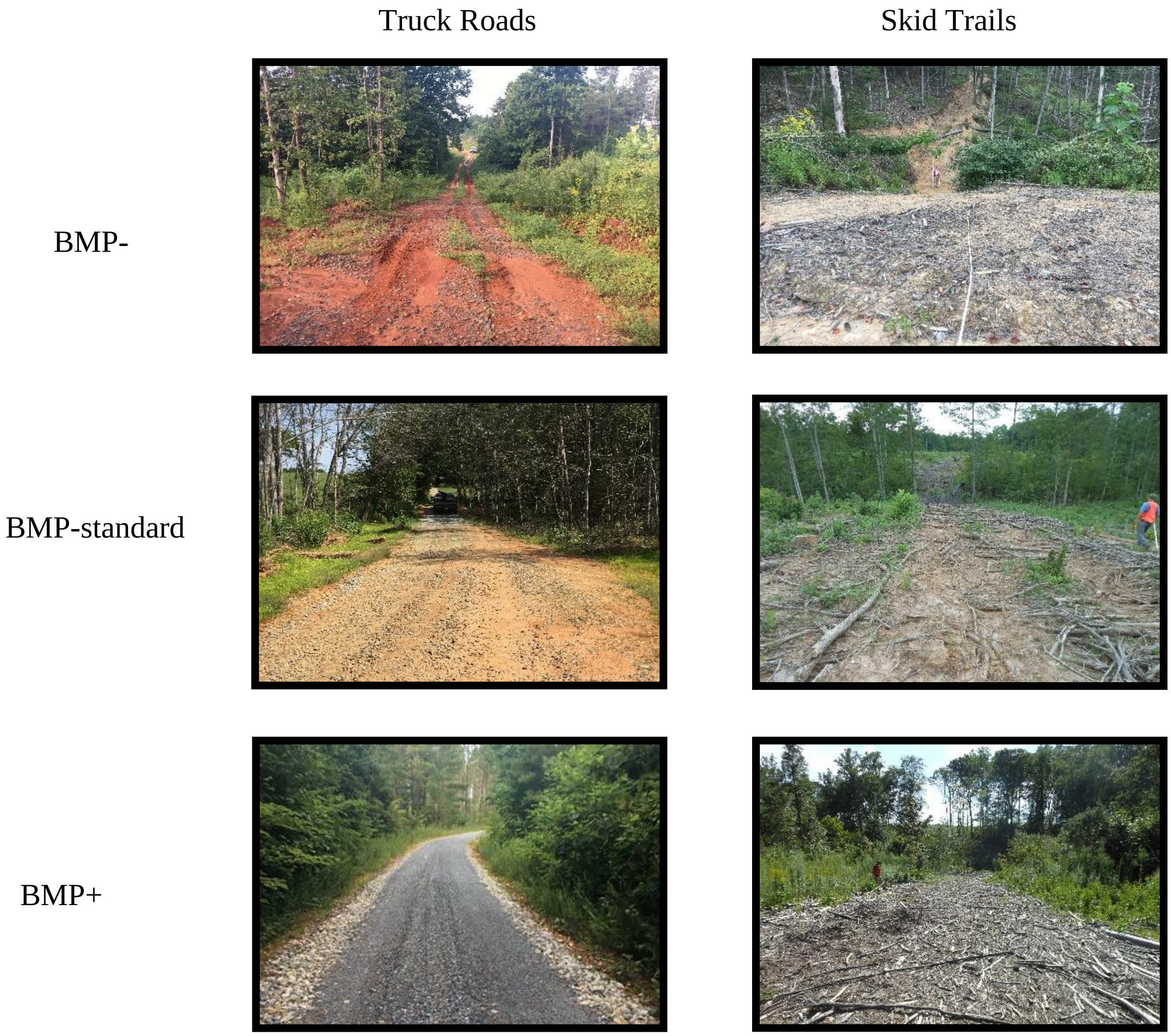

Figure 4.2. Representative stream crossing approaches for each BMP implementation level and road type.

Table 4.1. Criteria used to evaluate subcategories that determined overall BMP ratings at stream crossings.

Subcategory within BMP-standard	Criteria based on the VDOF BMP Manual
Road Template	• Stable approaches • Stable cut and fill slopes • Appropriate ditches and cross drains • Follows natural contour • Road gradient between 2-10% • Evidence of pre-harvest planning
Water Control	• Appropriate spacing between water bars or diversions • Working structures that are not collapsed or filled • Drains to SMZ or vegetated area
Stream Crossing Structure	• Stable fill above culvert with riprap • Appropriate culvert and bridge lengths • Correct sizing of culvert based on watershed size • Culverts are not perched nor inhibit aquatic species migration • Fords have a hard rock bottom or appropriate geoweb reinforcement • Stable streambanks • Crossing installed at a right angle
Surface Cover	• Ground cover is applied immediately after harvest close-out • Barriers such as hay bales, silt fences, and check dams are used if necessary • Ground cover is well-distributed

4.3.5 Analyses

To better understand the benefits and the drawbacks associated with executing and exceeding the manual recommendations, each BMP- and BMP-standard crossing was hypothetically upgraded either one or two times for consideration as a BMP+ crossing. BMP improvements were identified for both approaches for each crossing. Based on an earlier pilot study for this project (Nolan et al. 2015), the most common methods for reducing erosion rates are reducing slope length by increasing water control structures closer to the stream and adding ground cover to the approaches. In order to reflect these modifications in the USLE modelled erosion rates, we manipulated the LS factor and bare soil factor in the USLE-Forest equation.

Both of these methods were successfully used to hypothetically reduce rates of erosion by Nolan et al. (2015). Reconstruction of road template was not included in our hypothesized BMP upgrades because our recommendation was limited to those that a logger could be expected to conduct using available equipment and such construction activities could cause pulsed releases of sediment to the stream. Thus, such major construction activities were beyond the scope of the study. Other adequate improvements considered were the installation of a new culvert if the current one was undersized or collapsed, and the addition of geotextile or rock base to enhance a ford. However, the USLE cannot reflect the erosion values associated with these hypothesized improvements, therefore a cost-benefit analysis could not be performed in these cases.

Costs for additional water control structures, ground cover, and other closure expenses were estimated using the Virginia Tech Forest Road Costs Method (VTFRCM) modified by Conrad et al. (2012), which has been shown to estimate average costs for forest road construction and BMPs within 10% of the actual cost. Although gravel is an expensive ground cover option, it has been proven effective when adequately spread for a specific depth and distance (Swift 1986; Brown et al. 2015). Gravel costs per crossing were based on quarry derived estimates of \$27.56/delivered tonne (\$25/ton); gravel quantities were estimated by converting the density to mass by using the estimated volume required to cover the approach with a recommended depth of 7.6 centimeters (three inches) (Kochenderfer and Helvey 1987). Seed and mulch application costs were estimated based on costs per kilometer and subsequent conversion to \$ per square meter (Sawyers et al. 2012, Vinson et al. 2017b). Costs of slash application on skid trails were estimated using results from a recent survey of Virginia’s Piedmont loggers (Cole et al. 2017), with an average cost of \$1.91 per meter of trail. A cost-benefit analysis was performed by dividing the cost of the hypothesized improvements of a crossing by the change in erosion between the current and hypothetical erosion rates, which produced a value in dollars per megagram ($/Mg) of sediment prevented from entering the stream.

4.3.6 Statistical Analyses

JMP-Pro 13 was used to perform all statistical analyses at alpha level 0.05 (SAS Institute, Inc. 2016). As is common with operational research, data were not normally distributed, thus we analyzed data with a combination of descriptive statistics and nonparametric analysis, supplemented by regression. We determined means, medians, minimum, and maximum values for BMP levels within all regions and types of crossings, and we evaluated significant differences with nonparametric tests such as the Kruskal-Wallis test, followed by multiple comparisons using the Steel-Dwass all pairs test (Ott and Longnecker 2016). We also used regression to interpret the potential relationships found between BMP implementation percentages and potential erosion rates (Sugden and Woods 2007; Nolan et al. 2015).

4.4 Results

The Virginia Department of Forestry performs quarterly audits of timber harvests in each physiographic region of the state and reports the results each year. The questionnaire used by the VDOF to score stream crossing BMP implementation is presented in Table 4.2, which we incorporated into our sampling at every skid and truck crossing. Only questions applicable to the specific site and crossing were answered.

Table 4.2. Questions and response levels regarding 79 skid trail and 75 truck road stream crossings from VDOF Questionnaire; **bolded** questions were used to identify erosion specific issues and used in the adjusted regression.

Question	Mountains (%yes)		Piedmont (%yes)		Coastal Plain (%yes)	
	Skid	Truck	Skid	Truck	Skid	Truck
1. Are approaches stable and unlikely to contribute sediment to the stream?	73.1	92.0	76.0	76.0	100.0	88.0
2. Are culvert pipes installed properly in the channel to avoid undercutting and channel erosion?	66.7	93.3	50.0	78.9	0.0	65.0
3. Are culverts and bridges of adequate length?	83.3	82.4	87.5	71.4	94.1	90.0
4. Are culverts covered with adequate and appropriate fill material?	100.0	60.0	50.0	68.4	0.0	83.3
5. Are culverts covered with gravel to reduce erosion near the stream? (crossing)	100.0	86.7	0.0	73.7	0.0	73.7
6. Are culverts properly sized according the BMP manual Table 6 and 7 or Talbots formula?	66.7	73.3	50.0	73.7	100.0	70.0
7. Are fords used only where a natural rock base (or geoweb) and gentle approaches allow?	N/A	100.0	N/A	66.7	N/A	100.0
8. Are headwalls stabilized with vegetation, rock, or fabric to minimize cutting?	83.3	93.8	100.0	88.9	100.0	75.0
9. Are permanent bridge abutments adequate and stable?	N/A	N/A	N/A	100.0	N/A	N/A
10. Are stream banks and approaches reclaimed with sufficient vegetation, rock or slash?	84.6	92.0	84.0	84.0	96.4	84.0
11. Are stream crossings installed at or near right angles where possible?	92.3	100.0	100.0	100.0	96.4	100.0
12. Are temporary culverts, pole bridges, and bridges removed?	100	100.0	83.3	100.0	96.3	75.0
13. Are water diversion structures present where needed on approaches?	50.0	54.2	84.0	76.0	82.1	65.2

14. Do all ford crossings avoid restricting the natural flow of water?	N/A	100.0	N/A	100.0	N/A	100.0
15. Do all ford approaches have a 50-foot approach of clean gravel?	N/A	85.7	N/A	0.0	N/A	50.0
16. Do all ford crossings have underlying geo-textiles where needed on approaches?	N/A	N/A	N/A	0.0	N/A	N/A
17. Is the addition of unnatural materials in the stream to facilitate the use of a ford minimized?	N/A	100.0	N/A	100.0	N/A	100.0
18. Were pole bridges used only in appropriate circumstances?	92.8	N/A	100.0	N/A	100.0	N/A

Erosion rates were different among all BMP implementation levels (p<0.0001) and between truck road and skid trail crossings (p=0.002). Regionally, the Piedmont (p=0.0457) and Coastal Plain (p=0.0095) showed significant differences between truck and skid erosion rates, however the Mountain region did not (Table 4.3).

Table 4.3. USLE erosion rate (Mg/ha/yr) and audit score (%) mean and median values by road type and region. Values not followed by the same letter within a row are significantly different using the Mann-Whitney test at α = 0.05.

Erosion Rate	**Skid**				**Truck**			
	N	**Mean**	**Median**	**SD**	**N**	**Mean**	**Median**	**SD**
Mountains	26	11.9	2.2a	26.4	25	8.7	2.3a	12.6
Piedmont	25	8.2	1.0a	15.2	25	9.6	5.7b	10.0
Coastal Plain	28	6.8	0.4a	16.3	25	5.4	3.6b	4.1

Audit Score	**Skid**				**Truck**			
	N	**Mean**	**Median**	**SD**	**N**	**Mean**	**Median**	**SD**
Mountains	26	82.7	85.7a	17.6	25	86.2	88.9a	16.3
Piedmont	25	86.4	90.0a	19.3	25	79.2	90.0a	27.2
Coastal Plain	28	94.3	100.0a	11.2	25	80.3	87.5b	19.3

Audit scores were not significantly different by region without regard to road type, nor were road type scores significantly different without regard to region. Overall scores were significantly different among each BMP level (p<0.0001) (Table 4.4). Regionally, audit scores were only different by road type in the Coastal Plain (p=0.0032). Mean audit scores increased with each enhanced BMP implementation level.

Table 4.4. Audit score (%) distribution (18 questions) by region and BMP rating. Values not followed by the same letter within a column specific to a region are significantly different using the Steel-Dwass for all pairs test at α = 0.05.

		N	**Mean**	**SD**	**Min**	**Max**	**Median**
Mountains	BMP-	4.0	62.5	21.0	42.8	90.0	58.5a
	BMP_std	36.0	83.0	16.0	30.0	100.0	85.7a
	BMP+	11.0	97.1	5.0	88.0	100.0	100.0b
Piedmont	BMP-	9.0	42.4	22.8	20.0	83.0	33.0a
	BMP_std	30.0	89.8	12.3	60.0	100.0	90.0b
	BMP+	11.0	96.9	7.1	80.0	100.0	100.0b
Coastal Plain	BMP-	6.0	56.2	11.5	40.0	70.0	55.0a
	BMP_std	31.0	87.9	14.1	50.0	100.0	88.9b
	BMP+	16.0	99.1	3.6	85.7	100.0	100.0c

Erosion rates determined with the USLE-Forest equation decreased with increasing implementation, which are represented by rating category means and medians (Table 4.5). This trend occurred on both truck roads and skid trails in all regions.

Table 4.5. Erosion rate (Mg/ha/yr) distribution by region and BMP rating according to USLE-Forest. Values not followed by the same letter within a column specific to a region are significantly different using the Steel-Dwass for all pairs test at α = 0.05.

		N	**Mean**	**SD**	**Min**	**Max**	**Median**
Mountains	BMP-	4.0	51.4	49.6	2.4	117.8	42.8a
	BMP_std	36.0	7.8	12.8	0.0	57.9	2.9ab
	BMP+	11.0	3.5	8.2	0.1	28.2	0.7b
Piedmont	BMP-	9.0	21.9	20.9	3.3	69.0	18.8a
	BMP_std	30.0	7.8	8.8	0.1	33.6	5.5b
	BMP+	11.0	1.1	1.8	0.0	4.8	0.1c
Coastal Plain	BMP-	6.0	15.8	17.4	4.3	51.0	9.7a
	BMP_std	31.0	7.0	13.0	0.0	72.1	3.3a
	BMP+	16.0	1.0	2.0	0.0	8.2	0.1b

The WEPP: Road model yielded similar results to those of USLE, however this model generated less distinguishable categories of implementation (Table 4.6). Most values reported by WEPP were ultimately higher than those of USLE.

Table 4.6. Erosion rate (Mg/ha/yr) distribution by region and BMP rating according to WEPP: Road. Values not followed by the same letter within a column specific to a region are significantly different using the Steel-Dwass for all pairs test at α = 0.05.

		N	**Mean**	**SD**	**Min**	**Max**	**Median**
Mountains	BMP-	4.0	26.0	28.9	3.4	68.4	16.2a
	BMP_std	36.0	16.4	16.0	1.5	73.6	11.2a
	BMP+	11.0	18.8	14.5	7.7	58.5	14.0a
Piedmont	BMP-	9.0	24.3	22.7	4.4	76.1	15.6a
	BMP_std	30.0	21.8	14.0	1.6	57.4	19.0a
	BMP+	11.0	19.4	17.9	2.7	47.3	11.1a
Coastal Plain	BMP-	6.0	22.0	15.9	9.6	44.9	14.0a
	BMP_std	31.0	15.2	13.0	2.4	58.4	10.1a
	BMP+	16.0	11.5	6.8	1.5	24.8	10.9a

Potential erosion rates determined by the USLE were used to calculate cost-benefit ratios. To upgrade from a BMP- to BMP-standard, the cost-benefit ratio averaged $166.62/Mg for skid trails and $2274.22/Mg for truck roads. Table 4.7 depicts the differences in costs and benefits between truck roads and skid trails across BMP implementation levels.

Table 4.7. Average potential erosion rates and costs before and after hypothetical upgrades were made to truck road and skid trail crossings.

		Average before upgrade (Mg/year)	Average after upgrade (Mg/year)	Average cost/benefit ratio ($/Mg)	Average cost per crossing ($)
Skid	BMP-	1.93	0.33	166.62	36.06
	BMP_std	0.25	0.03	832364.02	62.23
	Average	0.30	0.06	750508.54	59.66
Truck	BMP-	0.52	0.28	2274.22	151.65
	BMP_std	0.25	0.05	322703.42	114.05
	Average	0.27	0.09	266411.81	120.66

There is a significant relationship between audit score and erosion rate for stream crossings overall (p<0.0001), and by road type: skid (p<0.0001) and truck (p=0.0202) (Figure 4.3). After reviewing the data, we adjusted the audit scores for each crossing to reflect erosion control BMPs by accounting for only the bolded questions in Table 4.2. Regionally, there were significant relationships between audit score and erosion rate for stream crossings overall in the

Mountains (p=0.005), and Piedmont (p=0.0142). The trend was not evident in the Coastal Plain, which had the highest average audit score (87.95%) and lowest average erosion rate (6.17 Mg/ha/yr) of the regions.

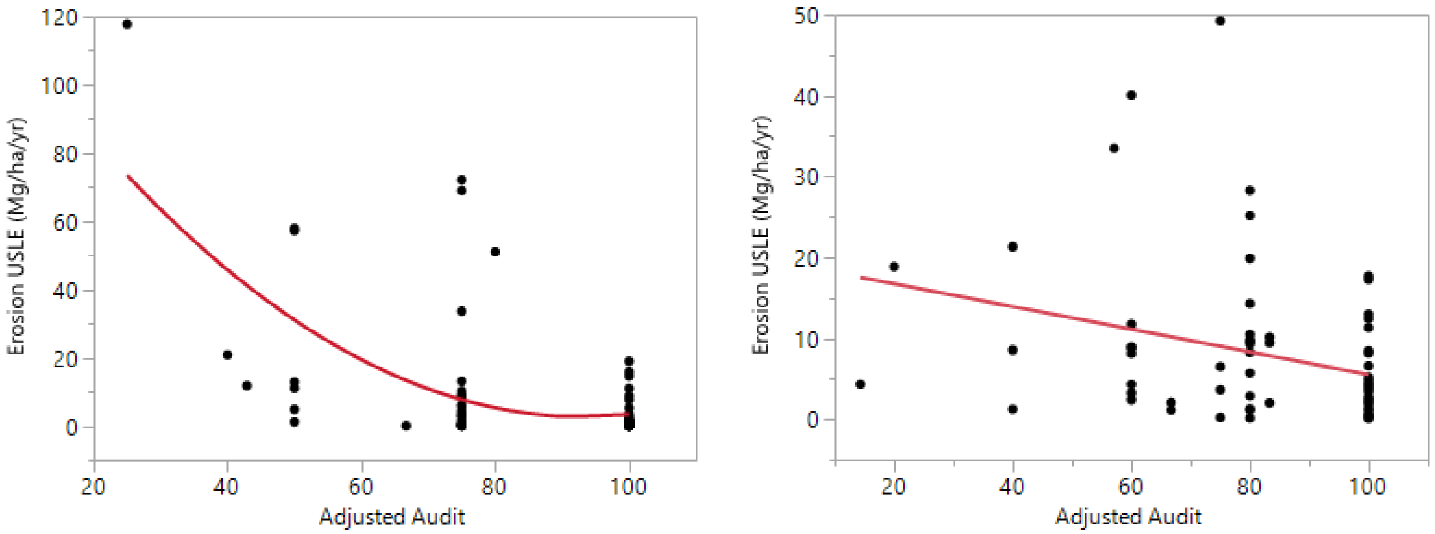

Figure 4.3. Linear regression of erosion rate versus audit score: Left: skid trails (r^2= 0.36, F = 21.00, p <0.0001). Right: truck roads (r^2 = .08623, p=0.0106).

In the Mountains, broadbased dips and water bars were used equally as frequently for water control purposes on truck roads, while water bars were most common on skid trails (Table 4.8). The Piedmont and Coastal Plain utilized water turnouts most often on truck roads, while skid trails in these regions most often used slash dams. All regions and road types had high percentages for absence of any water control structures.

Table 4.8. Distribution of water control structures for 302 approaches to stream crossings.

		Broadbased dip	Cross drain	Slash dam	Rolling dip	Sediment pool	Silt fence	Water bar	Water turnout	Tank trap	None
Mountains	Truck	14.60%	-	-	2.10%	2.10%	2.10%	14.60%	12.50%	-	52.10%
	Skid	-	-	3.50%	1.80%	-	-	33.30%	12.30%	1.80%	47.40%
Piedmont	Truck	7.10%	1.80%	1.80%	5.40%	8.90%	-	17.90%	26.80%	-	30.40%
	Skid	-	-	42.30%	1.90%	-	-	23.10%	5.80%	-	26.90%
Coastal Plain	Truck	13.70%	2.00%	-	2.00%	-	-	21.60%	23.50%	-	37.30%
	Skid	-	-	41.40%	-	1.70%	-	25.90%	6.90%	-	24.10%

All regions used gravel most commonly on truck roads, and the Mountains and Piedmont also utilized grass cover to close out truck roads (Table 4.9). In the Mountains, grass was the frequent form of ground cover on skid trails. Slash was most common on skid trails in the Piedmont and Coastal Plain. Mulch, as well as other combinations of alternative cover types were used among all regions and road types.

Table 4.9. Distribution of ground cover types on 302 approaches to stream crossings.

		Chips	Grass	Gravel	Local stone	Mulch	Natural veg or rock	Seed and mulch	Slash	Wooden mats	Logs	None
Mountains	Truck	3.80%	18.90%	58.50%	3.80%	3.80%	-	5.70%	1.90%	-	-	3.80%
	Skid	3.00%	30.30%	4.50%	-	15.20%	10.60%	6.10%	21.20%	-	6.10%	3.00%
Piedmont	Truck	-	21.90%	56.30%	-	3.10%	6.30%	7.80%	3.10%	1.60%	-	-
	Skid	-	5.80%	1.40%	-	2.90%	10.10%	5.80%	63.80%	-	10.10%	-
Coastal Plain	Truck	3.60%	9.10%	61.80%	-	14.50%	-	9.10%	-	-	-	1.80%
	Skid	-	7.80%	3.10%	-	6.30%	-	-	75.00%	-	3.10%	4.70%

Stream crossing structure distributions across regions didn’t vary substantially except by the preference of portable bridges on skid trails evident in the Piedmont and Coastal Plain but were not as widely preferred in the Mountains (Table 4.10). Culverts were the most abundant structure on truck roads in every region.

Table 4.10. Distribution of crossing structures by region and road type.

	Mountains		**Piedmont**		**Coastal Plain**		**Total**	
	Skid	**Truck**	**Skid**	**Truck**	**Skid**	**Truck**	**Skid**	**Truck**
Culvert	4	16	3	19	1	21	8	56
Improved ford	0	3	0	2	0	2	0	7
Permanent bridge	0	0	0	1	0	0	0	1
Pole bridge	13	0	6	0	11	0	30	0
Portable bridge	9	2	16	2	16	0	41	4
Unimproved ford	0	4	0	1	0	2	0	7

4.5 Discussion

4.5.1 Audits and Erosion

On average, for stream crossing BMP implementation, truck roads across all regions scored 82% and skid trails scored 88%. Based on our dataset, BMP implementation levels in the mountains should receive additional focus. Skid trails had lower BMP implementation and higher erosion rates in the Mountain regions. Thus, additional monitoring and training of loggers in mountainous regions might be beneficial. Use of enhanced BMPs might also be beneficial in this region. Secondly, all permanent stream crossings on truck roads had lower than desired BMP implementation ratings. These are a second operational area that could be targeted for additional training or enhanced BMP use. It could potentially be more beneficial to water quality if stream crossings and approaches became a priority for both monitoring and BMP upgrades. More specifically, both skid trails and truck roads lacked sufficient water control structures as evidenced by the BMP audit response (Table 4.2). Other identified deficiencies were inadequate culvert installation (question two), lack of appropriate fill material (question four), and improperly sized structures (question six).

Erosion rates trended inversely to BMP ratings, presenting significantly decreasing erosion rates with increasing BMP implementation level ($p = 0.0001$) (Tables 4.5 and 4.6). We initially expected to find a higher percentage of BMP- sites in the Mountains, but our hypotheses were not supported by the data. We did not find any major differences in erosion rates across regions ($p=0.3637$). These findings support the premise that BMPs are generally being applied correctly across all regions, despite differences in soil, topography, and logging practices. It is worth noting that when BMPs were not implemented, modelled erosion rates reflected the lack of management, but when BMPs were correctly implemented, no matter the choice of control structure or cover type, erosion rates decreased. These findings support the premise that a variety of different BMP approaches might be used successfully to achieve similar results.

The WEPP: Road platform was less satisfactory for identifying differences between BMP-standard and BMP+ levels than the USLE model. WEPP: Road also commonly estimated higher values than USLE (Table 4.6). Forest erosion estimates have been compared to direct measures of erosion on several road and trail studies (e.g. Brown et al.2013; Sawyers et al. 2012; Vinson et al. 2017a; Wade et al. 2012) and the values have been found to reflect erosion trends between BMP treatments even though actual quantities may vary. Our results from both models follow the general trend of decreasing erosion rates as BMP implementation increases (Figure 4.3). Lang et al. (2017) conducted a study in the Mountains and Piedmont and found that empirical models could predict erosion within five Mg if rates were less than 11.2 Mg/ha/yr.

4.5.2 Stream Crossings

Of the culverts sampled throughout the state on both truck roads and skid trails, 26.6% were elevated above the stream bed which limits aquatic species migration and habitat and leads to scouring of the streambed. Replacement culverts were recommended for 32.8% of all culvert installations due to reasons including corroded culvert bottoms, streams flowing under pipes, clogging, collapsed conditions, erosion of fill around pipe, and/or undersized culverts. These results indicate that additional emphasis on alternatives to culverts and correct installation and sizing of culverts might be beneficial. Most culvert data are from sampled truck roads rather than skid trails. Morris et al. (2016) compared the effectiveness of three levels of BMP treatments on three stream crossing structures (bridge, ford, and culvert). Rainfall simulations were used at differing levels of intensity to represent erosion in varying climate conditions. Two of the three crossings showed decreased sediment load with increased BMP level. The bridge crossing produced the least stream sediment during construction, but it was the most expensive treatment considered. However, the cost per use of a bridge is reduced when portable temporary bridges are re-used on multiple crossings. The lowest level of BMP bridge treatment (BMP-) was still a better option than the higher BMP level culvert and ford stream crossings tested for minimizing in-stream sediment concentrations.

Culvert and fords were primarily found on permanent truck roads because they can be more easily used for larger streams and watersheds and they have adequate load bearing potential. Bridges were found most often for skid trails in the form of pole bridges or temporary panels (Table 4.10). Without regards to road type, our data indicated one significant difference in erosion among stream crossing structures, which was between portable bridges and culvert crossings (p = 0.0353). Bridges have proven to be the least disruptive crossing type especially when temporary rather than permanent, most likely due to a preserved streamside management zone (SMZ) that provided shade to the stream (Aust et al. 2011).

4.5.3 Water Control and Cover

Stream crossings within all regions suffered from a lack of appropriate water control structures on truck roads (65%) and skid trails (73%), with only 69% of all crossings sampled having sufficient water control methods according to the BMP audit question 13 (Table 4.2, Table 4.8). Before reaching the stream, water diversion structures are commonly used to divert and slow water velocity so that soil detachment and transport is minimized. These structures are typically water bars and slash debris dams on skid trails, and water turnouts and broadbased dips on truck roads, but can also include sediment pools, rolling dips, and cross drained ditches. Our data indicate that water control crossings should be emphasized as a needed and underutilized stream crossing BMP.

Slash was the most abundant form of ground cover on skid trails in the Piedmont and Coastal Plain regions, while grass was the most abundant cover used in the Mountains. Slash was also the most common form of cover on skid trails rated BMP+. Erosion control measures include ground cover in the form of slash, gravel, grass, mulch, and combinations thereof. Silt fence, hay bales, and check dams are also common in ditches. These trends are present in the data (Table 4.9). In all regions and among all ratings on truck roads, gravel was the most commonly used ground cover. Results from Brown et al. (2013) indicate that completely graveled approaches yielded 7.5X less sediment than bare approaches to streams on legacy roads. Improper water control structures and/or insufficient ground cover caused the highest rates of sedimentation. They also found that poorly designed or maintained road networks can increase hydrologic connectivity (gullies and ditches), causing frequency and magnitude of flood flows to potentially increase. A change in timing and magnitude of rainfall events will produce more stormwater runoff, which can lead to fluvial geomorphic changes and degradation to aquatic habitat (Brown et al. 2013). A follow up study was conducted in 2015 using rainfall simulation experiments on a series of gravel-treated approaches of reopened roads. The study concluded that gravel application reduced TSS concentrations of road surface runoff (Brown et al. 2015).

Wade et al. (2012) determined the effectiveness of different levels of BMP prescriptions on six bladed skid trails at the Virginia Tech Reynolds Homestead Forest Resources Research Center in Patrick County, VA. A grass seed and mulch combination proved the most effective at trapping sediment, although there was no statistically significant difference between mulch and slash treatments. This study concluded that the bare minimum BMP (water bar) may not be sufficient on approaches that are steep or have naturally high erosion rates, and that ground cover is essential for reducing erosion following a harvest, especially during wetter periods of the year. Sawyers et al. (2012) assessed skid trail closure costs and effectiveness by using the same five treatments as Wade et al. (2012) on overland skid trails at Reynolds Homestead. They measured sediment loss, finding again, that the mulch treatment was the most effective at reducing erosion, with hardwood slash as the next best option. Wear et al. (2013) conducted a study at five harvest sites in the Virginia Piedmont, using similar treatments on stream crossing approaches: slash only, grass seed/mulch, grass seed/mulch/silt fence. Both slash and grass seed/mulch treatments effectively reduced total suspended solids. In addition, they found that the silt fence worsened the site conditions and increase the suspended solids concentration due to soil disturbance from installation. Three of these studies are in agreement that slash is the all-around best option to close out a skid trail. It takes the longest time to decompose, providing more cover for a longer amount of time, especially as grass can be difficult to establish depending on site conditions and season. It prevents unwanted travel (e.g. ATVs) and is usually the cheapest and easiest option for loggers as they complete operations.

4.5.4 Costs

Forest land ownership in Virginia is primarily held privately by individuals and families (62%) and corporations (19%) (Saulnier et al. 2017), and our data reflected this trend. Forest operations are generally conducted by contracted loggers with oversight provided by foresters, consultants, and landowners themselves (VDOF 2016b). Education has been an efficient tool to support sustainable harvesting, which is why many loggers in the state are Sustainable Harvesting and Resource Professional (SHARP) Logger trained, which allows them to deliver wood to mills having Sustainable Forest Initiative (SFI) certification. Stricter environmental regulations have been considered in recent court cases and water policy (Boston 2012), thus it is important to understand the potential costs that might be absorbed by contractors and landowners having to implement increased best management practices. In general, when considering both roads and skid trail crossings across all regions, BMP+ upgrades may not be worth the cost. Even with lower costs at the crossing itself, to reduce one Mg of sediment at the BMP+ level, average ratios were hundreds of thousands of dollars.

Skid trail enhancements for BMP- to a BMP standard was $36.00 on average, with a range of $4.58-$50.18, and average costs to upgrade a BMP-standard to a BMP+ was $62.23, with a range of $18.75-$249.00. The Mountain region would most likely benefit more than the other regions from improving BMP- sites to BMP-standard by spending an average of $13.59/Mg of erosion reduced. The general trends revealed by the cost-benefit ratios indicate that expenditure required to develop BMP+ levels do not prevent a significant amount of erosion, indicating that BMP-standard expenditures are more cost effective. However, absolute costs are low overall, so it is very possible that many loggers would be willing to invest in BMP+ level expenditures on skid trail crossings simply to ensure that they satisfy water quality inspections and enhance the professional appearance of the harvest.

Truck road BMP enhancements ranged from $18.75-$423.01, with an average price of $151.65 to upgrade from BMP- to BMP-standard. Costs to upgrade a BMP-standard to a BMP+ range from $18.75-$400, with an average of $114.05. There were no significant differences among regions in costs per crossing, nor was there a substantial difference in average costs for the upgraded categories. The results indicate that BMPs on truck roads can be applied at the recommended BMP level (BMP-standard) for a reasonable cost and can be upgraded once more to a BMP+ level by spending approximately twice as much. The Piedmont and Coastal Plain regions could experience reasonable benefits from upgrades in both categories, while the Mountains would benefit very little from upgrading to a BMP+.

4.6 Conclusions

The Virginia BMP audit scores for 2017 on 240 tracts reported 95.5% for stream crossings, which is a very good score and a substantial improvement from 81% over the past decade (VDOF 2017). Our data had an average score of 85% regarding stream crossings, which is significantly lower than the 2017 VDOF report. While the crossing audits are not separated by road type in the results, data pertaining to roads and trails in general is included. The questions that received the lowest scores regarded adequate gravel and/or vegetation to control erosion on forest roads (77.6%) and skid trails (47%), and proper water control diversion implemented at recommended distances for slopes on roads (70.8%) and skid trails (61%). Proper water diversion at stream crossings scored 89.9%. These categories that struggled to meet higher standards were evident in our data as well. While water control and ground cover BMPs are simple to grasp in theory, they are hard to implement in harsh weather conditions or on steep slopes and they can be neglected due to time constraints. Our study shows that these tasks are not an abnormal financial burden at the BMP-standard level, therefore more research is needed to investigate why these practices are the least successful and how they can be better executed. Major conclusions regarding our initial study objectives include:

1. Characteristics of the stream crossings sampled in each region of Virginia include an abundance of culverts used on truck roads (75%), while portable bridges (52%) and pole bridges (38%) are most commonly used on skid trails.
2. The overall cost-benefit ratio for truck roads ($2274.22/Mg) and skid trails ($166.62/Mg) to upgrade to state BMP requirements are reasonable. Skid trail first and second BMP

upgrades cost an average of $36.00 and $62.23, respectively. Truck road first and second BMP enhancements cost an average of $151.65 and $114.05, respectively. On truck roads, an average of 5.0 Mg/ha/yr was reduced after one upgrade, and an additional 4.9 Mg/ha/yr was reduced after two upgrades. On skid trails, an average of 31.4 Mg/ha/yr was reduced after one upgrade, and an additional 7.0 Mg/ha/yr was reduced after two upgrades.

3. Implementation rates for truck roads (82%) and skid trails (88%) were not significantly different. Median erosion rates were significantly higher on truck roads than skid trails in the Piedmont and Coastal Plain. This could be due to the need for continuous use of truck roads, as opposed to skid trails that are permanently closed with slash and water bars. Erosion rates were not significantly different in the Mountains.
4. Truck roads had implementation issues with culvert installation and maintenance. Truck roads and skid trails lacked sufficient water control structures in all regions.
5. The 2017 Virginia Department of Forestry BMP audit also recorded lack of working water control structures on roads, skid trails, and at stream crossings, along with insufficient ground cover. This study illustrates the need for proper water diversion and ground cover to control erosion effectively and clearly shows the opportunities to implement Virginia BMPs economically.

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