Effectiveness, Cost, and Implications of Forest Haul Road Stream Crossing Structures and Best Management Practices in Virginia

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ABSTRACT

Forest roads and stream crossings have the potential to be sources of sediment from forest operations. Recent litigation has renewed interest in furthering research related to forest road Best Management Practices (BMPs). Three legacy (100 year old) forest road stream crossings were monitored for suspended sediment for nine months before and six months after upgrading three unimproved ford crossings with one bridge, one culvert, and one improved ford. During construction, rainfall simulation was utilized to estimate the sediment contribution of each crossing with minimal BMPs (BMP-), BMPs equal to state recommendations (BMP), and BMPs beyond state recommendations (BMP+). Construction costs were recorded to quantify the change in cost with a change in BMP level. Three levels of rainfall simulation were used on each BMP treatment for each crossing resulting in 27 rainfall simulations. Water samples collected by an automatic sampler downstream of the crossings were analyzed for suspended sediment. Pre - and post- construction time periods were compared to assess how the improved crossings altered total suspended sediment concentrations downstream of the crossings. The number of stream crossings constructed per year in Virginia was also estimated using satellite imagery on 400 harvest tracts. Site visits were conducted on 240 harvest tracts where data were collected on the presence of crossings, the types of crossings, and the level of BMP implementation.

Rainfall simulation experiments showed decreased sediment with increased BMP level and daily total suspended sediment concentrations measured over 15 months showed a decrease in mean daily sediment concentration after construction of the bridge and culvert crossings. There was no decrease in sediment concentration for the ford crossing. Statewide crossing construction and BMP implementation rates were estimated. Approximately 67% of the audited stream crossings were characterized as having BMPs that were equal to or beyond state recommendations. Increased BMPs and upgrading of stream crossings resulted in decreased total suspended sediment. However, increased BMP implementation also increased stream crossing construction costs. Effectiveness of increased levels of BMPs and the pre and post construction analysis suggests the improvement of a legacy stream crossing may reduce total suspended sediment concentrations.

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1.0 Introduction and Literature Review

1.1 Introduction

Stream sediment which is eroded during forest operations is currently regulated as a non-point source pollutant. However, recent litigation has challenged the non-point status of this sediment source (Fletcher, 2011; Kennedy, 2013). This recent litigation has created interest in determining erosion and sediment control measures that are efficient, both for improving environmental benefit and reducing industry costs (Boston, 2012).

Stream crossings have been identified as an important link between forest road erosion and stream sediment (Taylor et al., 1999). Forest road stream crossings can be a sediment source (the road surface and fill material) and an erosion delivery mechanism that crosses the stream. Stream crossing structures and associated road approaches are an important link between forest road erosion and stream sediment delivery due to limited area to control surface water between the road surface and the stream. In order to differentiate the sediment associated with stream crossings and the road area leading to the crossing studies must be designed to isolate sediment that originates on the road approach from sediment which originates on the crossing structure (Taylor et al., 1999).

This research investigated the cost and sediment contribution of forest road stream crossings and potential levels of Best Management Practice (BMP) implementation in Virginia. The three levels of BMPs include BMP measures which do not meet the Virginia Department of Forestry recommendations (BMP-), BMP measures which are equivalent to state recommendations (BMP), and measure in addition to state recommendations (BMP+). The following research is comprised of three separate but related studies that determine the effects of three different crossing structures (bridge, culvert, and ford) and three levels of BMPs, the impact of stream crossing improvement on stream sedimentation, and quantification and characterization of stream crossings currently being installed and used in Virginia. The following literature review investigates the recent litigation, legislation, and literature regarding forest haul roads and stream sediment delivery. The negative effects of stream sediment are outlined giving background for the Federal Water Pollution Control Act (FWPCA)/Clean Water Act (CWA) and concerns that have been raised in recent litigation. BMPs have been developed, tested and implemented across the United States in an effort to meet the requirements of the FWPCA by reducing erosion and sedimentation from forest operations. The litigation, recent literature, economic, and environmental concerns lead into the overall objectives of this dissertation and the goals of each subsequent chapter.

1.2 Literature Review

1.2.1 Negative Effects of Stream Sediment

Timber harvesting has been shown to increase sediment levels which are common issues in terms of drinking water quality (Binkley and Brown, 1993). The future regulation and oversight of sediment produced from forest operations as a non-point source pollutant (NPSP) was questioned in recent litigation (Fletcher, 2011; Kennedy, 2013). Boston and Thompson (2009) proposed that the treatment of forest roads as NPSPs was not justified and that forest roads should be placed under the National Pollution Discharge Elimination System (NPDES). The main issue of concern is connectivity which is the ability of eroded material to be transported from the site of detachment to a watercourse or road drainage structure (i.e. ditches, ditch relief culverts and other drainage structures that concentrate water) which discharges into a watercourse. The recent court rulings (Fletcher, 2011; Kennedy, 2013) have created an opportunity for the forest industry to work with the regulatory community to develop methods of sediment reduction that are economically and environmentally effective (Boston, 2012). The renewed interest and controversy in the NPSP treatment for silvicultural operations illustrates that although the Federal Water Pollution Control Act (FWPCA) was enacted four decades ago, there is still a need to adequately quantify the costs and benefits, including social, industrial and environmental benefits and costs, of erosion prevention measures.

A recent review of literature (Anderson and Lockaby, 2011) in regard to sediment reduction from forest operations found gaps in research, including the quantification of BMP effectiveness and optimization of BMP applications for sediment reduction. It has been shown that BMPs are effective at reducing erosion and sedimentation (Arthur et al., 1998; Aust and Blinn, 2004; Ice et al., 2010; McKee et al., 2012; Sawyers et al., 2012; Wade et al., 2012); however, the optimal level of BMPs has not been adequately resolved.

The geologic norm for erosion in the eastern United States is <1 Mg ha^{-1} yr^{-1} (Patric, 1976) while road networks may produce a greater rate of erosion and sedimentation. For example, the Oak Creek watershed in Oregon has been shown to produce 14.8 Mg ha^{-1} yr^{-1} of sediment from the road network (Surfleet, 2011). At the Coweeta Hydrologic Laboratory in Otto North Carolina Riedel et al. (2007) found that road reconstruction which included the implementation of BMPs reduced stream sediment yields by 70%. Eroded material must be transported to a watercourse in order to be a threat to water quality. A field survey coupled with hydrologic modeling of ditch relief culverts in the Deschutes River Catchment in Oregon found 24% of drainage culverts were directly connected to streams with hill slope shape and distance to the stream being important variables (La Marche and Lettenmaier, 2001).

Studies of erosion and stream sedimentation associated with timber harvesting have focused on both the harvest area and the road network. Early studies showed sediment delivery in forested watersheds increased with a positive relationship between sediment yield and proportion of the watershed that has been clear cut and where roads have been constructed (Beschta, 1978; Reid and Dunne, 1984). Other studies have shown minimal effects on water quality following timber harvesting (Sullivan, 1985; Corner et al., 1996). Roads associated with pine plantation management have been found to be a much greater concern than the area of timber harvest in regards to sources of sediment from forest operations (Forsyth et al., 2006). While investigating rill and sediment plumes on United States Forest Service timber sales in California, Litschert and MacDonald (2009) found that 84% of the sediment producing features originated from skid trails while the remaining features originated in older clear cut harvest areas with minimal vegetation and coarse soils. The variability in results from these studies illustrates the variation in erosion due to other site specific conditions including soil type, topography, climate, etc. In addition to differences between studies and regions, Megahan (1972) found greater variability within plots than expected.

Flow volume and the flow generation processes can also alter both internal and external sources of stream sediment (Gomi et al., 2005). Water quality of stream water is often measured and used to determine negative effects of erosion; however, the use of aquatic species monitoring may result in a more holistic representation (Lane and Sheridan, 2002). The use of aquatic species monitoring as an accurate measure of the effectiveness of sediment reduction could be beneficial; however, the time associated with the monitoring of aquatic species could prove to be limiting.

1.2.2 Sediment Quantification

Methods for quantifying stream sediment from forest operations have focused on either in stream Total Suspended Sediment (TSS) sampling or upslope monitoring of erosion (Corner et al., 1996; Megahan, 1996, Brown et al., 2013, Wear et al., 2013). In-stream monitoring has been found to show large variability in sediment values (Binkley and Brown, 1993) as well as high cost due to sample processing requirements. As an example, Corner et al., (1996), found large variation with in-stream monitoring that resulted in a lack of statistically significant differences in erosion from silvicultural treatments in northeastern Washington, while upslope sediment traps resulted in statistically significant differences in erosion rates for the same treatment sites. Upslope sediment traps may have allowed for distinction between treatments in terms of volume of eroded material.

1.2.3 Best Management Practices

"Forestry Best Management Practices (BMPs) are methods, measures, practices, and techniques designed to maintain water quality from forested watersheds" (Aust et al., 1996). BMPs have been implemented throughout the United States and have shown to be an effective method for reducing impacts on water quality from forest operations (Briggs et al., 1998; Wynn et al., 2000; Shepard, 2006; Brown et al., 2013). BMPs that effectively control overland flow of water are able to minimize negative water quality effects (Aust and Blinn, 2004). By controlling overland flow by reducing overland flow velocity, BMPs are able to reduce erosion and reduce the proportion of eroded material that reaches a stream. BMPs that increase the interception of rainfall thereby decreasing detachment or reducing the transport capacity of runoff can control erosion, which can be accomplished through the application of vegetation and mulch type erosion control measures (Grace et al., 1998). BMPs have been shown to be effective at reducing erosion by controlling overland flow of water providing water/sediment storage capacity and reducing negative impacts of reduced infiltration rates and diverting overland flow to areas where sediment can settle without entering streams. National BMP implementation rates vary from state to state, however, in 2010 the national average, weighted for timber removal per state, was 89% (Ice et al., 2010). BMPs are constantly in need of updating based upon current research, as of 1997 many states had not incorporated long term research on the effectiveness of the BMPs into standards (Ice et al., 1997). However, more recently many states have implemented research programs investigating how well current BMPs achieve desired water quality standards (Ice et al., 2010).

Road design and layout may alter the presence and size of cut slopes and fill slopes as well as the gradient of a road. In Western Oregon, increases in slope and/or distance between erosion control structures, slope steepness and lack soil cover have been shown to increase erosion (Luce and Black, 1999). Increased surface cover allows for increased infiltration, reduced runoff and reduced erosion. Increases in surface cover also reduce raindrop impact which can lead to decreased surface sealing along with decreased evaporation when compared to bare soil (Adams, 1966). Erosion control measures on granitic cut-slopes in Idaho have resulted in statistically significant differences in erosion reduction when compared to the non-treated control (Megahan et al., 2001). Erosion on road cuts was found to be four times greater in the first year following construction than in the following seasons (Megahan et al., 2001). Erosion levels continued to increase two years post-harvest with a more pronounced increase on non-"reclaimed" sites, illustrating that both immediate and long term erosion control measures are necessary (Kochenderfer et al., 1997; Grushecky et al., 2009). These findings all reinforce the effect of slope length and gradient as well as surface cover and management practices outlined in the Universal Soil Loss Equation as adapted for forest lands (Dissmeyer and Foster, 1980).

Planning and layout can be major factors in reducing impacts to soil and water resources during timber harvest operations (Megahan, 1972; Kochenderfer et al., 1997; Worrell et al., 2011). Improving a previously built road in terms of erosion is difficult or impossible if the road was poorly located (Kochenderfer and Helvey, 1987). In addition to erosion impacts, lack of planning can increase harvest costs (Krueger, 2004). In Bolivia, tropical forest logging operations without pre-planned skid trails resulted in 8% of the skid trails used being unnecessary. Prior planning of skid trails resulted in a cost of $1.46/ha, but resulted in a return on investment of $3.00/ha, showing that increased planning costs may be returned through operational efficiencies and decreased disturbed area (Krueger, 2004). Unnecessary skid trails are also a common problem in Central Appalachia where proper planning could have reduced the number of forked and dead end skid trails, resulting in a decreased proportion of harvest area being disturbed (Kochenderfer, 1977). A review of research from 1982 to 2002 indicated that the water quality problems associated with forest harvesting are actually problems caused by poorly designed roads and skid trails, inadequate trail and road closures, stream crossings, excessive exposure to bare soil, or lack of adequate streamside management zones (Aust and Blinn, 2004). Increased soil bulk densities have been linked to machine passes on skid trails, showing that even one pass by a loaded rubber tired skidder can greatly increase soil bulk density illustrating the need for fewer but better planned, designated skid trails (Wang et al., 2005). The use of pre-harvest layout planning can result in decreased numbers and lengths of skid trails where the slopes traveled can be decreased and the number and location of stream crossings can be optimized.

Sawyers et al. (2012) found overland skid trail BMPs utilizing slash and straw mulch to be effective, however the use of grass seeding was found to produce a much smaller benefit in terms of erosion reduction due to failure of grass germination. The study used sediment trap data with monthly measurements which revealed minimal amounts of erosion (<1 Mg/ha) following the installation in late summer. However following the freeze thaw cycle of winter, the erosion rate increased and followed rainfall events. Wade et al. (2012) found similar results while investigating bladed skid trail BMPs in the Virginia Piedmont, with grass seeding performing better than a control that consisted of water bar only. The use of straw mulch and slash were both found to be effective at reducing erosion on bladed skid trails as well.

While investigating Vermont's Acceptable Silviculture Management Practices, Brynn and Clausen (1991) found that only 20% of skid trails contained the recommended number of water bars, but no skid trail showed evidence of advanced gullying (> 24 inches). They found rill erosion (up to 6 inches) on 20% of skid trails, initial gully erosion (6-12 inches) on 5% of the skid trails and marked gully erosion (12-24 inches) on 5% of the skid trails. The inconsistency between the proportion of skid trails with adequate BMPs and the proportion of trails with negative erosion impacts shows that prescriptive BMPs may not be necessary on all sites due to some of the trails without proper BMPs showing little sign of erosion. The difference between BMP implementation rates and skid trails showing signs of erosion found by Brynn and Clausen (1991) could help explain the benefit cost ratio range of 0.15 to 0.55 reported by Aust et al. (1996).

BMP implementation requires additional time from forest operators. In the mountains of Virginia, 5% of loggers surveyed spent less than one half day implementing BMPs, approximately 30% reported spending one half to one full day, approximately 45% reported spending one to two days, and less than 15% reported spending more than two days implementing BMPs (Bolding et al., 2010). In a 2001-2002 survey of West Virginia licensed loggers, 89% of respondents checked that they "always" follow BMPs. A 1996 survey of West Virginia logging operations found that only 58% of sites surveyed were in compliance with

BMPs for water bars, 55% of sites had skid trails that were seeded to BMP specifications, and only 19% of sites had used mulch to comply with BMPs (Egan et al., 1998). During a 2004-2005 survey, 99% of skid trails were found to be below 20% in slope, however only 63% had waterbars, 70% had been seeded, and 69% had been mulched (Wang et al., 2007). Non-compliance of BMPs can greatly increase the risk of soil loss and sedimentation of surface waters (Briggs et al., 1998).

Though involvement of a forester is correlated with increased BMP compliance, merely specifying BMP compliance in a timber sale contract was not correlated with BMP compliance (Egan, 1999). Egan (1999) found that landowner satisfaction was also found to be independent of BMP compliance due to the greater concern for time of harvest and stumpage price. Overly restrictive or unnecessary management practices such as excessive numbers of water control structures may cause logging operators to question BMPs in general (Brynn and Clausen, 1991). There must be a balance between financial costs of protection measures and the acceptable level of impact (Swift and Burns, 1999).

1.2.4 Stream Crossings and BMPs

Stream crossings are the most critical location for reducing erosion and sedimentation (Taylor et al., 1999). Stream crossings have been found to be major sediment sources in forested streams, but studies investigating the impact of various types of crossings are limited in both number and scope. Limitations in the scope are due to a lack of information regarding the sediment flux downstream during crossing installation and quantification of sediment from different types of crossings as well as specific sediment production from the crossing structure opposed to the road approach (Taylor et al., 1999). The areas of potential soil erosion include the stream crossing road surface and approach as well as drainage structures, cutslopes and fill slopes. However, the relative contribution of these areas vary due to differences in the sediment generation and transport differences of different materials on the fillslope, road surface and road approach (Lane and Sheridan, 2002). Stream crossing locations have been found to have a negative impact on stream water quality by increasing turbidity and suspended sediment with turbidity responding rapidly to rainfall events (Lane and Sheridan, 2002).

Lane and Sheridan (2002) found that the road fill slope and construction phase were the largest contributors to increases in suspended sediment. Aust et al. (2011) found that the period during forest operations resulted in a greater increase in downstream sediment when compared to pre harvest and post-harvest time periods. The construction period identified by Lane and Sheridan (2002) could be characterized as a period of increased soil and stream disturbance. Similarly the time period identified by Aust et al. (2011) as the harvest period would be characterized as a time with increased disturbance to the road approach and stream crossing. Additionally, Aust et al. (2011) suggested that although crossing types should be used where operationally feasible and appropriate, the crossing type could alter the erosion and sedimentation rates associated with the crossing.

The cost of crossing installation was found to be the least for an improved ford (estimated cost ranging from $100 to $1,000), culverts (estimated cost $200 to $1,500), followed by steel portable skidder bridges (temporary crossing costs estimated to be $2,000 to $4,000), permanent wooden bridges (estimated cost $5,000 to $40,000) and concrete and pipe low water crossing (estimated cost $10,000 to $50,000) (Visser et al., 2003). The concrete and pipe low water crossing constructed for the study was a large structure containing 12 corrugated steel pipes and 120 cubic yards of concrete. A 2009 survey (McKee et al., 2012) of Virginia loggers found that within the previous 12 months, 48% of loggers in the Piedmont region of Virginia had installed haul road stream crossings with 8% installing fords, 20% installing culverts, 12% installing wooden bridges and 20% installing steel bridges. The costs of these crossings including materials and installation were found to be $1,586 for culverts, $2,857 for wooden bridges and $11,246 for steel bridges. There was no cost estimate for fords in the Piedmont. However, in the mountains the average ford costs was $975. According to the survey results, there were no reinforced fords constructed during 2009.

Bridges are used as temporary and permanent forest road stream crossing structures and often produce less sediment than culverts (Thompson et al., 1995, Aust et al., 2011); however, they can be more expensive than other alternatives (McKee et al., 2012). While investigating methods for bridge scour countermeasures, Johnson and Niezgoda (2004) found three sources of sediment and erosion from bridges were noted, they include channel degradation that can be considered natural channel erosion, contraction scour that is caused by the narrowing of the channel by abutments and piers and local scour that occurs at piers and abutments. Additionally, Aust et al. (2011) identified the road approach as a potentially significant source of erosion and sediment. Forest road bridges are often short enough to minimize the use of piers and abutments are often comprised of the native stream banks which would eliminate channel contraction scour and local scour. However, use of rip-rap to armor the banks may narrow the channel, leading to contraction scour. Rip-rap is the most common form of bridge abutment armor; however, it can fail due to rock being carried downstream or soil erosion underneath the rip-rap (Johnson and Niezgoda, 2004).

Use of culvert pipes allows for traffic to pass without contacting the stream bed or water reducing direct input of sediment from traffic. However, the use of culvert pipes has been shown to result in channel scour at the outlet of the culvert pipe (Mendoza et al., 1983; Lim, 1995).

Although a culvert minimizes the sediment impact from road traffic, the impact of the construction phase of all crossing types is not well documented (Taylor et al., 1999). To minimize the erosion due to scour at the outlet of culverts the Virginia Department of Forestry recommends the following BMPs; 1) the culvert should be placed at the same gradient as the natural stream bed, 2) the pipe should extend one foot beyond the edge of fill on both ends, and 3) 10% of the culvert diameter should be below the elevation of the native stream bed (VDOF, 2009). The effectiveness of stream crossing structures and associated BMPs to reduce sediment has been studied with several different methods including rainfall simulation.

Rainfall simulation allowed for the identification of the main sources of sediment from culvert crossings in Australia to be the road surface, fill slope and the construction phase (Lane and Sheridan, 2002). These sources of erosion resulted in TSS and turbidity values downstream 2 to 3 times that of the upstream measurements. Jordán and Martínez-Zavala (2008) used rainfall simulation to estimate the soil loss from road surfaces, road cut banks and fill slopes. Road cut banks were found to have a soil loss rate of 5-6 times that of the road surface or fill slope. The increased soil loss was likely due to the presence of loose soils and limited vegetative cover. The use of logging slash as a surface cover to aid in erosion reduction and grass seed germination have been shown to reduce erosion (Rothwell, 1983; Wade et al., 2012; Sawyers et al., 2013). In the case of Rothwell et al. (1983), the grass was found to germinate faster and the volume of erosion was decreased when slash was applied to the stream crossing fill and cut slopes. The use of surface cover including slash, mulch, grass seeding and rock/gravel could reduce the erosion potential for the sediment sources identified by Lane and Sheridan (2002). Further study of the efficiency of BMPs through more intensive monitoring of operational impacts is needed, specifically covering more diverse, less controlled systems (Binkley and Brown, 1993).

1.2.5 Economics of Erosion and Sediment

Wind and water erosion prevention measures in the United States have been estimated to cost $13.1 billion (2014 US Dollars), however if these measures could reduce the average rate of erosion from 38 Mg ha^{-1} yr^{-1} to 2.2 Mg ha^{-1} yr^{-1} the reduction in sediment damages would total $68.5 billion (2014 US Dollars), resulting in a cost to benefit ratio of 1:5.24 (Pimentel et al., 1995). The same study estimated the water related costs of sediment in streams to be $7.9 billion per year in the United States with costs being attributed to impacts on recreation ($3.7 billion), water-storage ($1.3 billion) and navigation ($1.1 billion). Biological impacts of stream sediment are acknowledged, but are not assigned a dollar value. Other economic impacts of sediment in streams are attributed to flood damages, water conveyance facilities and water treatment facilities. The sum of all annual costs of both in stream and out of stream impacts of sediment has been estimated to be $13.1 billion (Pimentel et al., 1995). Nation-wide direct costs of sediment removal in the water treatment industry have been estimated to range between $812 million and $2.43 billion annually. This is based upon the treatment costs of $57.08 to $171.23 per million gallons of water processed (Holmes, 1988). These two studies have reported a large range values for the economic impact of stream sediment, $7.9 billion (Pimentel et al., 1995) and a range from $812 million to $2.43 billion (Holmes, 1988). Economic losses due to sediment and erosion coupled with the relatively low cost of erosion reduction measures suggests that there is a societal net benefit to reducing erosion and sedimentation.

While investigating agricultural water pollution control programs Young and Magleby (1987) found benefit-cost ratios ranging from 0.1 to 1.8 suggesting that in some areas the cost of mitigation measures may outweigh the benefit in pollution reduction. In this case, the application of erosion prevention measures at some sites resulted in economic benefits of approximately 10% of the cost while other sites produced financial benefits of 180% of the prevention costs. Aust et al. (1996) found benefit-cost ratios for Virginia forestry BMPs ranging from 0.15 to 0.55 and concluded that targeting areas with a high risk can increase the effectiveness of BMPs. The use of simple BMPs may be adequate to mitigate erosion and pollution issues from many watersheds where the risk is relatively low, however, in other areas the use of extensive pollution abatement methods may be economically viable (Young and Magleby, 1987).

When analyzing the costs of forestry BMPs Sun (2006) found that the welfare of forest products consumers was decreased due to increased costs of environmental regulation that is passed from the landowner and logger, through the processing facility and to the final consumer. This analysis did not include societal benefits from improved water quality or other environmental benefits. The decrease in welfare of consumers is due to the increased costs of BMPs implemented during harvesting. BMP implementation on US Forest Service timber sales in the Midwest (Illinois, Michigan, Minnesota, Missouri and Wisconsin) has been shown to result in a harvest cost increase of up to 6.5% (Ellefson and Miles, 1985). Using the logic described by Sun (2006) this 6.5% increase in harvest costs could be passed along to the end consumer in the form of higher prices for pulp and paper products as well as solid wood products.

Concerns regarding state forest practice recommendations and regulations (i.e. BMPs) are generally not related to whether there should be protection, but they questioning how much protection is necessary (Henly et al., 1988). The costs associated with forest regulation and BMP programs comes both in terms of regulatory and administrative costs to the state and local agencies as well as industry costs to landowners, loggers and eventually consumers. In order to best serve society, a balance must be found in which the cost of regulation and practices are justified by the benefit. Sediment delivered to streams several decades ago may be responsible for water quality issues in the future as the sediment travels downstream (Duda, 1985). Jackson et al. (2005) estimated that the sediment associated with late 1800s and early 1900s farming in the Piedmont could take six to ten millennia to remove and for the past 50 years the Murder Creek Watershed has been in a state of net sediment export. This continued water quality degradation may reduce the benefit of sediment reduction activities in use at the present time or near future.

1.2.6 Summary and Conclusions

BMPs have been found to be effective at reducing erosion; however, there has been little work to determine economic optimal levels of BMPs for various areas including haul road stream crossings. BMPs for erosion reduction include applying surface cover through the use of straw mulch, slash or sowing grass seed as well as proper planning to minimize the slope of roads and trails and avoiding sensitive areas. Avoidance of sensitive areas during planning stages could result in better location of stream crossings, reducing slope or allowing for a better road alignment, reducing potential erosion. The effects of BMPs vary across studies and regions suggesting that the application of one set of BMPs for all scenarios may not be appropriate due to other factors leading to erosion. The use of BMPs can be regulatory or voluntary, though the use of regulatory or voluntary systems is not reflected in compliance rates and the use of BMPs is crucial for the overall effectiveness of BMPs. BMPs must be designed with cost as a consideration and they must provide the greatest protection for water quality possible while minimizing the cost in order to increase compliance.

Recent litigation has lead industry and government agencies to look for both environmentally and economically sound measures to minimize sediment input from forest operations. In order to mitigate the regulatory concerns, the solutions to the problem must reduce sediment while minimizing the cost of implementation, minimizing the implementation cost to land owners and managers. The problem becomes a basic benefit-cost issue with the cost being attributed to construction and implementation of sediment reducing BMPs as well as the cost of mitigation measures and the benefit being the reduction in sediment and the associated increase in recreational and intrinsic value associated with an improvement in water quality.

1.3 Objectives and Organization

Forest harvesting operations have utilized BMPs since the 1970's; however, they are still an area of concern regarding water quality, cost and litigation. In order for land managers and policy makers to continue to make well informed decisions regarding forest haul road stream crossings and the appropriate levels of BMPs, further work on the effectiveness of BMPs on stream crossings should be conducted. Research was conducted to estimate both stream crossing BMP effectiveness and costs at an individual stream crossing scale and state wide scale.

Specific objectives of the study are to:

- Estimate sediment reduction efficiency of common stream crossing BMPs on bridge, culvert and ford stream crossings (Chapter 2),
- Document cost of common stream crossing BMPs on bridge, culvert and ford stream crossings (Chapter 2),

- Determine how upgrading legacy unimproved ford stream crossings with a designed bridge, culvert and ford with BMPs beyond state recommendations may alter stream sediment (Chapter 3),
- Estimate total number of permanent forest haul road stream crossings installed in Virginia each year by crossing type and BMP level (Chapter 4).

This dissertation is organized into five chapters. Chapter one is an introduction and literature review. Chapters two through four were prepared as manuscripts which are to be submitted for publication to appropriate peer-reviewed journals. Chapter five then draws conclusions for this dissertation and gives recommendations for future research. Chapter two is titled *Levels of forestry best management practices used for stream crossing structures affect sediment delivery and installation costs*. This manuscript is authored by Brian C. Morris, M. Chad Bolding, W. Michael Aust, Kevin J. McGuire, and Erik B. Schilling and is prepared for submission to the Elsevier journal *Forest Ecology and Management*. The manuscript is prepared for submission in the summer of 2015. Chapter three is titled *Sedimentation following legacy forest road stream crossing improvement and best management practice installation* and is authored by Brian C. Morris, M. Chad Bolding, W. Michael Aust, Kevin J. McGuire, and Erik B. Schilling. Chapter three was prepared as a manuscript to be submitted to the Society of American Foresters' peer-reviewed journal *Forest Science* in the "Applied Track" in the summer of 2015. Chapter four is titled *An approach for estimating the number of forest road stream crossings in Virginia*. This manuscript is authored by Brian C. Morris, M. Chad Bolding, W. Michael Aust, Kevin J. McGuire, Erik B. Schilling, and Jay Sullivan. Chapter four has been prepared as a manuscript to be submitted for publication in the Society of American Foresters' peer-reviewed journal *Forest Science* in the "Applied Track" in the summer of 2015.

1.4 Literature Cited

Adams J. E. (1966) Influence of mulches on runoff, erosion and soil moisture. Soil Science Society of America Journal. 30:110-114.

Anderson C., Lockaby B. (2011) Research gaps related to forest management and stream sediment in the United States. Environmental Management 47:303-313.

Arthur M. A., Coltharp G. B., Brown D. L. (1998) Effects of best management practices on forest streamwater quality in eastern Kentucky. Journal of the American Water Resources Association 34:481-495.

Aust W. M., Carroll M. B., Bolding M. C., Dolloff C. A. (2011) Operational forest stream crossings effects on water quality in the Virginia piedmont. Southern Journal of Applied Forestry 35:123-130.

Aust W. M., Blinn C. R. (2004) Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years. Journal of Water, Air and Soil Pollution 4:5-36.

Aust W. M., Shaffer R. M., Burger J. A. (1996) Benefits and costs of forestry best management practices in Virginia. Southern Journal of Applied Forestry 20:23-29.

Beschta R. L. (1978) Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14.6:1011-1016.

Binkley D., Brown T. C. (1993) Forest practices as nonpoint sources of pollution in north america1. Journal of the American Water Resources Association 29:729-740.

Bolding M. C., Barrett S. M., Munsell J. F., Groover M. C. (2010) Characteristics of Virginia's logging businesses in a changing timber market. Forest Products Journal 60:86-93.

Boston K. (2012) Impact of the ninth circuit court ruling (Northwest Environmental Defense Center v. Brown) regarding forest roads and the Clean Water Act. Journal of Forestry 110:344-346.

Boston K., Thompson M. (2009) An argument for placing logging roads under the NPDES program. Ecology Law Currents 36:169-176.

Briggs R. D., Cormier J., Kimball A. (1998) Compliance with forestry best management practices in Maine. Northern Journal of Applied Forestry 15:57-68.

Brown K. R., Michael Aust W., McGuire K. J.(2013) Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia piedmont. Forest Ecology and Management 310:836-846.

Brynn D. J., Clausen J. C. (1991) Postharvest assessment of Vermont's acceptable silvicultural management practices and water quality impacts. Northern Journal of Applied Forestry 8:140-145.

Corner R. A., Bassman J. H., Moore B. C. (1996) Monitoring timber harvest impacts on stream sedimentation: Instream vs. Upslope methods. Western Journal of Applied Forestry 11:25-32.

Dissmeyer G. E., Foster G.R. (1980) A guide for predicting sheet and rill erosion on forest land. Technical Publication SA-TP-11, USDA Forest Service – State and Private Forestry Southeastern Area.

Duda A. M. (1985) Environmental and economic damage caused by sediment from agricultural nonpoint sources. Journal of the American Water Resources Association 21:225-234.

Egan A. F. (1999) Reducing forest road erosion: Do foresters and logging contracts matter? Journal of Forestry 97:36-39.

Egan A. F., Whipkey R. D., Rowe J. P. (1998) Compliance with forestry best management practices in West Virginia. Northern Journal of Applied Forestry 15:211-215.

Ellefson P. V., Miles P. D. (1985) Protecting water quality in the midwest: Impact on timber harvesting costs. Northern Journal of Applied Forestry 2:57-61.

Fletcher W. A. (2011) Northwest environmental defense center v. Brown, 640F.3d 1063. United States 9th Circuit Court of Appeals.

Forsyth A. R., Bubb K. A., Cox M. E. (2006) Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain pinus plantation. Forest Ecology and Management 221:194-206.

Gomi T., Moore R., Hassan M. A. (2005) Suspended sediment dynamics in small forest streams of the Pacific Northwest. Journal of the American Water Resources Association 41:877-898.

Grace J. M., Rummer B., Stokes B. J., Wilhoit J. (1998) Evaluation of erosion control techniques on forest roads. Transactions of the ASABE 4:383-391.

Grushecky S., Spong B. D., Mcgill D. W., Edwards J. W. (2009) Reducing sediment from skid roads in West Virginia using fiber mats. Northern Journal of Applied Forestry 26:118-121.

Henly R. K., Ellefson P. V., Moulton R. J. (1988) Evaluating state regulation of private forest practices: What accomplishments at what costs. Evaluation and Program Planning 11:325-333.

Holmes T. P. (1988) The offsite impact of soil erosion on the water treatment industry. Land Economics 64:356-366.

Ice G. G., Schilling E. B., Vowel J. G. (2010) Trends for forestry best management practices implementation. Journal of Forestry 108:267-273.

Ice G. G., Stuart G. W., Waide J. B., Irland L. C., Ellefson P. V. (1997) Twenty-five years of the Clean Water Act: How clean are forest practices? Journal of Forestry 95:9-13.

Jackson C.R., Martin J.K., Leigh D.S, West L.T. (2005) A southeastern piedmont watershed sediment budget: Evidence for a multi-millennial agricultrual legacy. Journal of Soil and Water Conservation 60:298-310.

Johnson P. A., Niezgoda S. L. (2004) Risk-based method for selecting bridge scour countermeasures. Journal of Hydraulic Engineering 130:121-128.

Jordán A., Martínez-Zavala L.(2008) Soil loss and runoff rates on unpaved forest roads in southern Spain after simulated rainfall. Forest Ecology and Management 255:913-919.

Kennedy A.M. (2013) Decker v. Northwest Environmental Defense Center, 133 S. Ct. 1326, 568 U.S., 185 L. Ed. 2d 447. Supreme Court of the United States.

Kochenderfer J. N. (1977) Area in skid roads, truck roads, and landings in the central appalachians. Journal of Forestry 75:507-508.

Kochenderfer J. N., Edwards P. J., Wood F. (1997) Hydrologic impacts of logging an Appalachian watershed using West Virginia's best management practices. Northern Journal of Applied Forestry 14:207-218.

Kochenderfer J. N., Helvey J. D. (1987) Using gravel to reduce soil losses from minimum-standard forest roads. Journal of Soil and Water Conservation 42:46-50.

Krueger W. (2004) Effects of future crop tree flagging and skid trail planning on conventional diameter-limit logging in a bolivian tropical forest. Forest Ecology and Management 188:381-393.

La Marche J. L., Lettenmaier D. P. (2001) Effects of forest roads on flood flows in the Deschutes River, Washington. Earth Surface Processes and Landforms 26:115-134.

Lane P. N. J., Sheridan G. J. (2002) Impact of an unsealed forest road stream crossing: Water quality and sediment sources. Hydrological Processes 16:2599-2612.

Lim S. Y. (1995) Scour below unsubmerged full-flowing culvert outlets. Proceedings of the ICE - Water Maritime and Energy 112:136-149.

Litschert S. E., Macdonald L. H.(2009) Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. Forest Ecology and Management 259:143-150.

Luce C. H., Black T. A. (1999) Sediment production from forest roads in western Oregon. Water Resources Research 35:2561-2570.

McKee S. E., Shenk L. A., Bolding M. C., Aust W. M. (2012) Stream crossing methods, costs, and closure best management practices for Virginia loggers. Southern Journal of Applied Forestry 36:33-37.

Megahan W. F. (1972) Logging, erosion, sedimentation--are they dirty words? Journal of Forestry 70:403-407.

Megahan W. F. (1996) Predicting downslope travel of granitic sediments from forest roads in Idaho. Water Resources Bulletin 32:371-382.

Megahan W. F., Wilson M., Monsen S. B. (2001) Sediment production from granitic cutslopes on forest roads in Idaho, USA. Earth Surface Processes and Landforms 26:153-163.

Mendoza C., Abt S. R., Ruff J. F. (1983) Headwall influence on scour at culvert outlets. Journal of Hydraulic Engineering 109:1056-1060.

Patric J. H. (1976) Soil erosion in the eastern forest. Journal of Forestry 74:671-677.

Pimentel D., Harvey C., Resosudarmo P., Sinclair K., Kurz D., McNair M., Blair R. (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117-1123.

Reid L. M., Dunne T. (1984) Sediment production from forest road surfaces. Water Resources Research 20:1753-1761.

Riedel M.S., Swift L.W.Jr., Vose J.M., Clinton B.D. (2007) Forest road erosion research at the Coweeta Hydrologic Laboratory. In *Advancing the fundamental sciences: Proceedings of the Forest Service National Earth Sciences Conference*, ed. M. Furniss, C. Clifton, and K. Ronnenberg, 197-204. PNW-GTR-689. Portland, OR. United States Department of Agriculture Forest Service, Pacific Northwest Research Station.

Rothwell R. L. (1983) Erosion and sediment control at road-stream crossings. The Forestry Chronicle 59:62-66.

Sawyers B. C., Bolding M. C., Aust W. M., Lakel W. A. (2012) Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia piedmont. Journal of Soil and Water Conservation 67:300-310.

Shepard J. P. (2006) Water quality protection in bioenergy production: The US system of forestry best management practices. Biomass & Bioenergy 30:378-384.

Sullivan K. (1985) Long-term patterns of water quality in a managed watershed in Oregon: Suspended sediment. Journal of the American Water Resources Association 21:977-987.

Sun C. (2006) Welfare effects of forestry best management practices in the United States. Canadian Journal of Forest Research 36:1674-1683.

Surfleet C. G. (2011) Road runoff and sediment sampling for determining road sediment yield at the watershed scale. Canadian Journal of Forest Research 41:1970-1980.

Swift L. W., Burns R. G. (1999) The three R's of roads: Redesign, Reconstruction, and Restoration. Journal of Forestry 97:40-44.

Taylor S. E., Rummer R. B., Yoo K. H., Welch R. A., Thompson J. D. (1999) What we know -- and don't know -- about water quality at stream crossings. Journal of Forestry 97:12-17.

Thompson J. D., Taylor S. E., Yoo K. H., Brinker R., Tufts R. A. (1995) Water quality impacts from different road stream crossings. Presented at the Council on Forest Engineering - Sustainability, Forest Health and Meeting the Nations Needs For Wood Products, (1995) Corvallis, OR.

Virginia Department of Forestry. (2009) Virginia's forestry best management practices for water quality.Virginia Department of Forestry, Charlotsville, VA.

Visser R., Aust W. M., Gallagher T., Roberts T., Poirot M. (2003) Cost of six different stream crossing options in the Appalachian area. Southern Journal of Applied Forestry 27:66-70.

Wade C. R., Bolding M. C., Aust W. M., Lakel W. A. (2012) Comparison of five erosion control techniques for bladed skid trails in Virginia. Southern Journal of Applied Forestry 36:191-197.

Wang J., Ledoux C. B., Edwards P., Jones M. (2005) Soil bulk density changes casued by mechanized harvesting: A case study in central Appalachia. Forest Products Journal 55:37-40.

Wang J., Mcneel J., Gogg W., Milauskas S. (2007) Assessment of compliance of forestry best management practices in West Virginia. Southern Journal of Applied Forestry 31:60-65.

Wear L. R., Aust W. M., Bolding M. C., Strahm B. D., Dolloff C. A. (2013) Effectiveness of best management practices for sediment reduction at operational forest stream crossings. Forest Ecology and Management 289:551-561.

Worrell W. C., Bolding M. C., Aust W. M. (2011) Potential soil erosion following skyline yarding versus tracked skidding on bladed skid trails in the Appalachian region of Virginia. Southern Journal of Applied Forestry 35:131-135.

Wynn T. M., Mostaghimi S., Frazee J. W., McClellan P. W., Shaffer R. M., Aust W. M. (2000) Effects of forest harvesting best management practices on surface water quality in the Virginia coastal plain. Transactions of the ASABE 43:927-936.

Young C. E., Magleby R. S. (1987) Agricultural pollution control: Implications from the Rural Clean Water Program. Journal of the American Water Resources Association 23:701-707.

2.0 Levels of Forestry Best Management Practices Used for Stream Crossing Structures Affect Sediment Delivery and Installation Costs

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2.1 Abstract

Forest road stream crossings have potential to negatively affect stream water quality and current best management practices (BMPs) may be improved through additional measures. Three levels of forestry BMPs (BMP-, BMP, and BMP+) were applied to three legacy forest road stream crossings (panel bridge, culvert, improved ford) on similar Virginia Piedmont intermittent streams. BMP- treatments were minimal BMPs that did not meet Virginia's existing BMP guidelines. BMP treatments met the state recommendations while BMP+ treatments exceeded state recommendations. After each BMP level was applied to each stream crossing, three simulated rainfall intensities (low, medium, high) were applied in order to evaluate the sediment delivery from each crossing type and BMP level. Sediment delivery associated with each crossing was collected with automated water samplers. Costs (materials, supplies, labor, and equipment) for each stream crossing and BMP gradation were also quantified. During rainfall simulation, sediment concentrations (mg/L) were collected and water yields (L/s) were estimated to calculate total sediment loading. Ford, culvert and bridge crossings produced 13.04, 12.95, and 0.17 Mg of sediment during construction, respectively. The greatest sediment delivery during the 30 minute rainfall simulation (5.25 Mg) was produced by the BMP- ford. The culvert with BMP+ produced the least amount of sediment, 0.90 Mg, during the 30 minute rainfall simulations. The bridge BMP- treatment produced the least sediment for the bridge

crossing (0.96 Mg). The addition of BMP and BMP+ treatments on the bridge resulted in increased sediment (1.16 Mg and 1.31 Mg, respectively) The best cost effectiveness ratio occurred with the ford and standard BMP ($124 Mg^{-1} of sediment reduction) while the culvert with BMP- resulted in the poorest cost effectiveness ratio ($2,590 Mg^{-1} of sediment reduced). The cost effectiveness and total sediment reduction observed during rainfall simulations suggests that the current BMP requirements are effective at reducing stream sedimentation while minimizing costs.

2.2 Introduction

Forest operations generally have few long term effects on water quality, but forest roads, skid trails, and stream crossings have long been areas of concern (Patric, 1976; Yoho, 1980; Kochenderfer and Helvey, 1987; Binkley and Brown, 1993; Lakel and Poirot, 2013). Stream crossings are a particular problem and have been shown to alter stream temperature, decrease dissolved oxygen concentrations and increase sedimentation (Binkley and Brown, 1993). The United States Environmental Protection Agency regards sediment from forest operations as a non-point source pollutant (NPSP). However, 2013 litigation in federal circuit courts, appeals courts, and the United States Supreme Court (Kennedy, 2013) considered the possibility of treating forest roads as point sources of pollution, which would require federal permitting under the National Pollution Discharge Elimination System (NPDES). A recent review of forestry BMPs and sediment by Anderson and Lockaby (2011) identified gaps, including quantification of the effectiveness of BMPs and the optimization of BMP applications for sediment reduction. Taylor et al. (1999) found the distinction between sediment produced on upslope road approaches and stream crossings to be unclear, pointing out a need for studies which can separate the sources of sediment. The recent series of court rulings have provided impetuous for collaboration between forest managers and the regulatory community to identify and enhance methods of sediment reduction that are economically and environmentally effective (Boston, 2012).

The geologic norm for erosion in relatively undisturbed forest lands of the eastern United States is generally less than 1 Mg ha^{-1} yr^{-1} (Patric, 1976; Yoho, 1980; Pimentel et al., 1995), but forest road systems can severely increase both erosion and sediment delivery. Numerous research projects identified forest roads as a primary factor controlling sediment from forest operations (Megahan, 1972; Croke and Mockler, 2001; Croke et al., 2005; Surfleet, 2011). Trimble and Sartz (1957) conducted one of the earlier studies that evaluated how the proximity of forest roads to streams can increase sediment loading. Several of the early hydrologic watershed studies conducted on United States Forest Service Experimental Forests concentrated on the evaluation of forest roads and sediment (Kochenderfer, 1970; Douglass and Swank, 1972; Ursic, 1991). In general these evaluations have detected minimal long lasting negative effects following timber harvesting alone, yet increases in sediment yield have been correlated with increased road building associated with timber harvesting (Beschta, 1978; Reid and Dunne, 1984) .

2.2.1 Best Management Practices (BMPs)

Forestry Best Management Practices (BMPs) are methods which are implemented to minimize negative water quality impacts from forested watersheds (Aust et al., 1996). BMPs typically are designed to minimize the factors which contribute to erosion or to direct the erosion into areas where it can be deposited before entering a stream (Aust and Blinn, 2004). Following inception of the Federal Water Pollution Control Act of 1972, many states developed BMP guidelines for the protection of water quality which have been shown to be effective (Arthur et al., 1998; Aust and Blinn, 2004; Ice et al., 2010; McKee et al., 2012; Wade et al., 2012). The situation is exacerbated by what Peirce (1980) describes as a lack of "standards" for non-point source pollution based upon water quality, in addition to the poor documentation of impacts of sediment pulses from forest operations on aquatic species (Sheridan and Noske, 2007). In 1997, state implemented BMP effectiveness monitoring was found to be lacking (Ice et al., 1997). However in 2010, many states had implemented effectiveness monitoring programs (Ice et al., 2010).

BMPs that maintain or increase the soil cover, increase interception of rainfall, and reduce soil particle detachment are typically effective erosion control measures. Such erosion control BMPs are epitomized by the retention of soil litter layers, re-establishment of vegetation, and application of soil cover like mulch or slash (Grace et al., 1998). Erosion control measures, including dry seeding, hydroseeding plus mulch and terracing with hydroseeding and mulch, on granitic cut-slopes in Idaho resulted in significantly less erosion when compared to the non-treated control road segments (Megahan et al., 2001). The use of a gravel surface cover of 34-60% and 50-99% on haul road stream crossing approaches was found to reduce sediment by 2.6 and 3.5 times, respectively, from a no gravel treatment (Brown et al., 2015). Sawyers et al. (2012) found BMPs utilizing slash and straw mulch to be effective for erosion control on overland skid trails; however, the use of grass seeding only was less effective for erosion reduction. Wade et al. (2012) found similar results while investigating bladed skid trail BMPs in the Virginia Piedmont; straw mulch or slash treatments perform better than grass seeding and waterbar only treatments. The use of gravel on haul roads as well as vegetation establishment from grass seeding on low volume haul roads have been shown to decrease erosion rates when compared to bare soil controls (Swift, 1984; Kochenderfer and Helvey, 1987; Brown et al., 2013;

Brown et al., 2015). Edwards and Williard (2010) evaluated three studies of BMP efficiency for sediment reduction and found that the efficiency of BMPS as well as total sediment loads decreased with time since harvest.

Thompson et al. (1995) examined sediment produced from three Piedmont stream crossings (two bridges and one culvert) during the construction phase and after installation. This study found it was difficult to separate the effects of stream crossing road approaches from effects of the actual stream crossing. The need to separate the road approach and the stream crossing erosion problems was also raised by Taylor et al. (1999). Overall, Thompson et al. (1995) found that the bridge stream crossing produced less sediment than the culvert crossing, but they also concluded that the BMPs used on the approach were as important as the type of stream crossing used.

In Virginia, stream crossings have been identified as an area of concern regarding BMP effectiveness and implementation (Lakel and Poirot, 2013). Aust et al. (2011) evaluated 23 stream crossings in the Piedmont of Virginia representing a range of crossing types and permanency. They concluded that culvert crossings and permanent crossings tended to result in lower downstream water quality, but also concluded that all crossings types could be adequate when suited to the crossing situation and appropriate BMPs applied. This was supported by Wear et al. (2013) who evaluated the closure BMPs used for 9 panel bridge skid trail stream crossings on harvest sites in the Piedmont of Virginia and found that slash or mulch could be effectively used to close stream crossings.

A 2009 survey of Virginia loggers found that 48% of surveyed loggers in the Piedmont region of Virginia had installed haul road stream crossings within the previous year (McKee et al., 2012). Bridges (wooden and steel panel were the dominate crossing type (32%), followed by culverts (20%) and fords (8%). Costs of materials and installation for these crossings averaged $1,586 for culverts, $2,857 for wooden bridges, and $11,246 for steel bridges. No cost estimate was provided for fords in the Piedmont; however, in the Mountains the average ford cost was $975. Visser et al. (2003) investigated stream crossing installation costs for four stream crossings in the Ridge and Valley physiographic region of Virginia. Costs were the least for an improved ford crossing a 1.2 m wide intermittent stream, followed by panel bridges crossing a 7.3 m wide perennial stream, and a low water crossing constructed over a 24.4 m wide perennial stream.

Haul road stream crossing structures (i.e. bridges, culverts, fords, etc.) each have different potential sediment contributions. However, each crossing type may only be suitable in certain crossing locations and situations (Aust et al., 2011). Culverts are relatively simple to install, have moderate costs, and can be installed to bear heavy loads with simple designs. Disadvantages include disturbance of the natural stream bed, modification of the stream cross sectional area and increased water velocity at outlets (Mendoza et al., 1983; Lim, 1995). Bridges can be expensive, but portable bridges can be used for multiple crossings over time. Fords have the advantage of relatively low cost if the streambed can bear heavy loads and handle most flood events (McKee et al., 2012). Disadvantages of fords include traffic limitations during high flows and in-stream sediment disturbance associated with traffic entering the stream channel.

2.2.2 Stream Crossing BMPs

Application of erosion control measures on road surfaces (Brown et al., 2013) and the use of forested stream buffers have been found to be effective for reducing erosion and stream sediment (Lakel et al., 2010). Stream crossings result in an increased potential for sedimentation due to the road crossing through the stream buffer at the stream crossing (Lakel et al., 2010).

Lane and Sheridan (2002) conducted a rainfall simulation experiment to quantify the principle sources of sediment from a culvert crossing (e.g. road surface, fill slope and construction phase). They evaluated upstream and downstream total suspended solids (TSS) and turbidity values for stream crossings and found a two to three fold increase in TSS and turbidity for their culvert crossing.

The use of brush mulch or logging slash as a surface cover to aid in erosion reduction and grass seed germination has been shown to reduce erosion from culvert stream crossings (Rothwell, 1983). In this case study, the grass was found to germinate faster and the volume of erosion was decreased when brush mulch was applied to the stream crossing fill and cut slopes. The use of surface cover including brush mulch and grass seeding and rock/gravel could reduce the erosion potential for the sediment sources identified by Lane and Sheridan (2002). Aust et al. (2011) found that haul road stream crossings met or exceeded the state BMP standards on 78% of harvest tracts. They also found that bridges resulted in the least impact upon water quality; however, they were not able to differentiate between sediment which originated on the approach and which originated on the crossing structure.

Recent litigation (Fletcher, 2011) and surveys of BMP compliance (Lakel and Poirot, 2013) have focused attention of forest stream crossings and forest stream crossings have the potential to contribute disproportionately large quantities of sediment to streams compared to their actual area. Despite concerns and the costs of implementing BMPs, there have been few studies investigating the direct impact of various stream crossing structures or stream crossing BMPs on sediment levels that separate the effects of the stream crossing from the effects of the road approach (Taylor et al., 1999).

This case study was designed to quantify the sediment delivery and cost of stream crossing structures associated with BMPs. Specifically, this study: 1) estimated downstream sediment loading following simulated rain events on crossings with various levels of BMPs; 2) assessed the effectiveness of BMPs and estimated a benefit-cost ratio for BMP implementation on three haul road stream crossings; and, 3) determined the cost per reduction of sediment for crossing installation and additional BMPs.

2.3 Materials and Methods

2.3.1 Site Description

The study was conducted on Virginia Tech's Reynold's Homestead Forest Resources Research Center in Patrick County, VA (36°38'58" N, 80°9'16" W) located along the western edge of the Piedmont physiographic region. Typical forest management in the area includes loblolly pine (*Pinus taeda*) plantations, natural Virginia pine (*Pinus virginiana*), and mixed hardwood stands. An existing legacy road at Reynold's Homestead Forest Resources Research Center crosses intermittent streams in three locations. The legacy forest road is in excess of 100 years old, has fair to poor location, surfacing, and water control. A bridge, culvert, and ford were constructed with three levels of BMP treatments on the three stream crossings. Preceding this experiment all streams had been crossed with un-designed ford stream crossings having soft bottoms and steep approaches. The watershed area above the three crossings consists of mature mixed hardwood forests. Watershed areas for the bridge, culvert, and ford crossings were 40.4, 17.0, and 32.4 ha, respectively (Table 1). During construction activities the costs of materials, labor, and equipment were recorded to determine the cost of crossing construction and BMP treatments.

Table 1: Stream characteristics by crossing structure installed. Watershed area measured from crossing location. Stream slope, full bank width and depth measured immediately upstream of installed crossing location. All three crossing locations had a stream bed slope of 2%. Stream bed material composition based upon a 40 bed material samples.

Crossing	Watershed Area (ha)	Full Bank Width (m)	Depth at Full Bank (m)	Bed Material Silt/Clay (%)	Bed Material Sand (%)	Bed Material Gravel (%)	Bed Material Cobble (%)	Bed Material Boulder (%)
Bridge	40.4	2.65	0.28	10.0	27.5	45.0	17.5	0.0
Culvert	17.0	2.29	0.16	7.5	25.0	42.5	25.0	0.0
Ford	32.4	3.41	0.26	7.3	19.5	46.3	19.5	7.3

2.3.2 Initial Road Preparation and Crossing Selection

Before stream crossing installation, each stream was evaluated so that the culvert, bridge, and ford were most appropriately suited to stream characteristics. The stream crossing location with vertical banks was selected for the bridge crossing. A ford was installed where the channel was wide and the approaches were shallow. The culvert treatment was applied at a stream location where the channel was defined. The legacy road approaches were modified to improve alignment for the crossings by shifting the road centerline to allow for the crossing to be as close to perpendicular to the stream channel as feasible. All three crossings were first constructed with a minimal level of erosion prevention measures (BMP-) that were considered complete when they could be navigated by a log truck, representing the bare minimum crossing improvement work that would be required for forest operations to utilize the crossing.

2.3.3 Construction – Bridge

The original legacy ford stream crossing consisted of steep approaches with poor alignment. The poor alignment required vehicles to negotiate a curve while entering and exiting the stream channel. These difficult travel conditions often required four-wheel drive and resulted in substantial channel disturbance. In order to improve trafficability and reduce maintenance and risk of erosion from the road network, a wood panel bridge was installed. The bridge consisted of three white oak (*Quercus alba*) panels; 7.3 m long, 1.2 m wide and 0.2 m thick. The panels were combined to form a bridge 7.3 m in length and 3.6 m wide (Figure 1). The bridge spans a distance of 2.8 m with approximately 2.25 m of bridge extending beyond the abutments on each side. The eastern abutment for the bridge was constructed using two gabion baskets (0.9 m x 0.9 m x 3.6 m) that were placed along the edge of the stream channel. Approximately 0.6 m of fill was required behind the gabion baskets to allow for the desired grade on the bridge approach. The eastern abutment utilized a near vertical stream bank that was stabilized by the roots from surrounding trees. Geo-textile was applied on both abutments. Approximately 5 cm of Virginia Department of Transportation (VDOT) #5 (1.25 – 5 cm stone) drain rock was applied on the geotextile to aid drainage and increase the longevity of the permanent bridge.

Figure 1: Left, bridge during rainfall simulation on BMP+ treatment with gabion basket as an abutment (left of stream) and the road running surface and bare soil rocked. Right, bridge prior to application of rock over the geo-textile on the running surface of the road (BMP), picture shows geo-textile prior to rock application which completed the BMP treatment, rock was applied over the geo-textile.

2.3.4 Construction – Culvert

The culvert crossing replaced a legacy road ford with steep approaches and a soft non-reinforced stream bed which often required four-wheel drive for travel. The alignment of the road leading to the crossing resulted in excessive curvature. The relocation and realignment of the road centerline shifted the location of the culvert approximately 10 m below the original ford. The relocation improved the horizontal curvature of the road, thereby improving both trafficability and grade of the approaches. The VDOF BMP guidelines suggested using a 0.9 m (36 inch) culvert for the 17 ha watershed and a 10-year return interval storm event. Two 6.1 m (20 foot) culverts were joined into a 12.2 m (40 foot) pipe. This length facilitated desired road alignment and provided sufficient length to allow gentle fill slope ratios above the culvert. For installation, the stream channel was excavated using a New Holland TN750 farm tractor with a 3-point mounted backhoe. The culvert was aligned with the native channel with approximately 1/3 of the culvert being below the natural stream bed to allow for course bed load material to fill the bottom of the pipe and facilitate travel of aquatic species. Fill material was moved and compacted with a John Deere JD450 bulldozer. Upon completion of the earth work, the bulldozer was used to compact and grouser track the fill slopes which increased surface roughness and storage.

2.3.5 Construction – Improved Ford

An existing un-improved ford on the legacy road was reinforced and improved. The existing ford had a semi-rocky bottom. The road was not perpendicular to the stream channel and the upstream tire track in the stream was often soft, resulting in vehicle tires sinking several inches into sediment which had settled in the wheel track. The crossing was improved by re-aligning the road to allow for a crossing that is near perpendicular. The steep stream banks were sloped to allow for an easier transition when traveling through the crossing. The stream bed was reinforced utilizing Geo-Web to stabilize the VDOF specified VDOT #5 gravel which was placed in the stream channel. In order to maintain the native stream gradient the stream bed was excavated 15.2 cm. After the Geo-Web was placed in the excavated area, it was backfilled with VDOT #5 gravel to the top of the Geo-Web.

2.3.6 BMP Level Treatments

The condition of the crossing immediately after installation comprised the BMP-treatment in which sub-guideline BMPs were used and the only requirement for construction was the ability to travel the road safely in a log truck (Table 2). The first BMP level (BMP-) did not meet the Virginia Department of Forestry (VDOF) BMP requirements (VDOF, 2009) and contained minimal erosion mitigation. The second BMP treatment level (BMP) provided the standard BMP guidelines recommended by the VDOF; however, no additional erosion mitigation measures were used. The final BMP level (BMP+) was designed to represent an increased level of erosion protection. The BMP+ treatment surpassed the requirements of the VDOF as confirmed by site visits by multiple VDOF water quality inspectors. Although the BMP+ methods were in excess of recommended guidelines the treatments had been previously implemented on operational forest roads in Virginia and were therefore considered feasible.

Table 2: BMP treatment description by crossing type. Rock on road surface #357 (1.90- 2.54 cm) stone, rock in stream bed (used in Geo-Web) is VDOT #5 (1.25-5 cm) stone and rock on fill slopes is #3-0 size stone (approximately 10-30 cm stone).

Stream Crossing	BMP-	BMP	BMP+
Ford	Sloped Banks, Bare Road Surface, Bare Fill	Sloped Banks, Rocked Road Surface, Rocked Fill	Geo-Web, Rocked Stream Bed, Rocked Road Surface, Rocked Fill
Culvert	Bare Road Surface, Bare Fill	Rocked Road Surface, Bare Fill	Rocked Road Surface, Rocked Fill, Mulch, Seed
Bridge	Bare Road Surface, Bare Fill	Rocked Road Surface, Bare Fill	Rocked Road Surface, Rocked Fill

2.3.7 Rainfall Simulation

Three intensities of rainfall simulations were conducted on all three stream crossing types and all three BMP treatments providing a total of 27 simulations. Rainfall simulations utilized an 18 horsepower centrifugal pump with a suction hose 10 cm in diameter and 6 m in length. Water was pumped from a downstream pond through a 7.6 cm fire hose for 15.2 m, 30.4 m, and 45.7 m for the bridge, culvert, and ford crossings, respectively. Water pressure at the pump was maintained at 345 kPa. The fire hose supplied water to a 5.1 cm PVC manifold which divided the water into eight 1.6 cm hoses (2-4 m in length). This supplied water to eight 2.5 cm by 3.1 m PVC risers fitted with Wobbler® sprinkler heads. The sprinkler heads utilized an interchangeable nozzle that allowed for simulation of three separate rainfall intensities: Low – nozzle diameter of 2.38 mm (mean rainfall rate of 1.8 cm hr^{-1}); Medium – nozzle diameter of 3.97 mm (mean rainfall rate of 5.5 cm hr^{-1}); and High – nozzle diameter of 5.56 mm (mean rainfall rate of 5.8 cm hr^{-1}). Sprinkler risers were arranged to maximize the uniformity of rainfall and minimize rainfall application to the surrounding area that was not part of the crossing. Each rainfall simulation was conducted for 30 minutes.

At the bridge crossing, the first series (high, medium, low intensity) of rainfall simulations were conducted on the BMP- treatment, which was characterized by a drivable bridge with no erosion control measures. The road surface and all bare soil were left bare within the simulation area. The second rainfall simulation series were conducted on the BMP treatment which consisted of the application of geo-textile for 20 m on each side of the bridge surface with approximately 5 cm of #357 stone (1.25-5 cm stone) on the entire road running surface within the simulation area. The final rainfall simulations were conducted on the BMP+ treatment which was characterized by all bare soil being covered and armored with rip-rap (approximately 10-30 cm stone).

For the culvert stream crossing, the initial rainfall simulations were conducted on the BMP- treatment, which consisted of the fully constructed culvert with bare soil on the road surface and fill slopes. The second series of rainfall simulations were applied to the BMP treatment, which consisted of the application of #357 rock to the road running surface on top of Geo-textile. The final treatment that received rainfall simulation, BMP+, consisted of applying rip-rap to the fill slopes as well as the application of grass seed and straw mulch to the bare soil near the road surface and fill slopes (Figure 2).

Figure 2: Culvert after installation and during BMP- rainfall simulation (Left), Culvert prior to BMP+ rainfall simulation with rocked running surface and fill slopes and seed and mulch on bare soil (Right).

Figure 3: Ford crossing with BMP+ treatment including rocked running surface and Geo-Web in the channel.

For the ford crossing, the beginning rainfall simulations commenced with the BMP- treatment. For BMP- the stream banks were angled and smoothed with the backhoe to allow for easier travel through the crossing and approaches were graded with a bulldozer. BMP- resulted in approximately 50% bare soil due to the native rock fragment. The second series of rainfall simulations were conducted on the BMP treatment. BMP treatment did not improve the stream-bed; however #357 rock was applied to the running surface of the approaches. The final series rainfall simulations were conducted on the BMP+ treatment in which Geo-Web and rock were applied to the stream channel and all bare soil near the crossing was covered with native stone or gravel (Figure 3).

2.3.8 Stream Crossing Construction and BMP Implementation Costs

Material, labor and equipment costs were recorded during the initial construction and subsequent BMP implementation for each stream crossing. Labor and equipment hours were recorded to the nearest ½ hour. Labor costs were calculated based upon a rate of \$20 US hour^{-1}. The \$20 rate assumes an hourly wage of \$13 hour^{-1} with an additional 50% of the wage being attributed to employer costs (i.e. workers compensation insurance). Bulldozer and backhoe hourly rates were obtained for local earth moving contractors in Patrick County, Virginia. The local contract rate for a bulldozer was \$95 hour^{-1} and the backhoe rate was \$65 hour^{-1}. Hourly rates include all fuel, maintenance and lubrication expenses as well as operator wages and transportation costs of equipment. Excavator costs for the bridge construction were based upon the billed hourly rate of \$85 hour^{-1}. The bulldozer and backhoe were owned and operated by the Reynolds Homestead while the excavator was a private contractor. The equipment and labor costs are representative of the region; however, each individual landowner/contractor may have slightly different labor and equipment costs based upon location, experience of employees and equipment variables such as size and age of machines.

2.3.9 Stream Total Suspended Solids Measurement

Total suspended solids (TSS) were sampled upstream and downstream of all stream crossings during the construction phase and rainfall simulation experiments using ISCO 3700 automatic water samplers. Samplers were placed 20 m upstream and 20 m downstream of the crossing locations similar to the approach used by Wear et al. (2013) for skidder stream crossings in the same region. During construction, the upstream samplers collected at noon while the downstream samplers collected samples on 30 minute intervals from the beginning to the end of construction activities. During rainfall simulations, the upstream samplers collected samples on 10 minute intervals with the first sample being taken at the beginning of the simulation experiment and continuing for 30 minutes after the rainfall simulation had ceased. The downstream sampler collected samples on 5 minute intervals, beginning with the start of the rainfall simulation and continuing for 30 minutes after rainfall had ceased. Samples were collected at the end of each day and transported to storage. Laboratory samples were processed similarly to the method outlined by Eaton et al. (2005). Samples were vacuum filtered through pre-weighed 1.5 micron fiberglass TSS filters. Filters with sediment were dried for 24 hours at 105°C before being weighed. TSS concentration was calculated by subtracting the pre-filter weight from the post filter weight and dividing by the volume of water filtered.

Stream stages were recorded at upstream and downstream sampling locations utilizing Onset HOBO U20 water pressure and temperature loggers. Data were collected on one minute intervals during rainfall simulations and 5 minute intervals during construction activities. An additional HOBO U20 logger was used to record barometric pressure and correct stage measurements for barometric pressure fluctuations. Stream discharge was determined using through state-discharge relationships that were calculated by comparing stage measurements with discharge measurements using a salt dilution method (Moore, 2004; Moore, 2005). Mean discharge measurements at base flow conditions were used to calculate sediment mass. TSS concentration (mg/L) and stream discharge (L/s) were multiplied to calculate total mass of sediment (Mg/s) contributed during construction and rainfall simulation events.

The streams were of similar dimensions, watershed size, land cover, and previous land use. We also monitored the stream sediment levels above and below the proposed crossing for nine months and found similar pretreatment sediment conditions. Within each crossing type, we were restrained to applying the lowest level of treatment and rainfall simulation before progressing to the next level of BMP treatment. Thus, BMP treatments were not randomized. Finally, in order to achieve increased soil moisture conditions, rainfall simulations were progressed from highest to lowest.

2.3.10 Data Analysis

In-stream sediment deliveries were calculated from the stream sediment concentrations collected during and after rainfall simulation events and the stream discharge observed during the times in which the water samples were taken. Operational studies of this magnitude and expense are not as easily addressed with conventional experimental designs, thus we have limited our interpretations to Analysis of Variance and post-hoc means tests. The data were tested for normality and transformed using a log transformation to allow for ANOVA and the Tukey-Kramer HSD means comparisons tests. Significant differences from the ANOVA were based on $\alpha=0.05$. When treatment effects were found to have significant differences the Tukey-Kramer HSD test (Zar, 1999) was subsequently utilized to separate differences between treatment means (α=0.05). Analysis of variance was utilized with BMP level (3 levels) and error as the sources of variation. Each BMP level consisted of three rainfall simulations on three crossings with approximately 12 water samples per simulation.

2.4 Results

2.4.1 Construction and BMP Costs

2.4.1.1 Bridge Costs

The bridge installation was completed with 42.5 person hours of labor, 2 hours of bulldozer use, 7.5 hours of backhoe use, and 4 hours of excavator work. The total cost for the BMP- bridge purchase and installation was $5,368, but could have been reduced to $5,058 if the gabion baskets were not used (Table 3). The BMP addition of gravel to the road running surface resulted in a cost increase of 5% while the BMP+ addition of Rip-Rap resulted in an additional 4% increase in cost. It should be noted that the bridge was installed as a permanent crossing, although the panels we used are similar to those often used for portable bridges. Thus, these costs represent a permanent haul road bridge crossing.

Table 3: Crossing and BMP construction materials and costs required for construction of a wood panel bridge.

BMP Level	Materials	Quantity	Cost/Unit	Total Cost
BMP-	Bridge	1	$2,325	$2,325
	Bridge Transportation (hours)	7	$85	$595
	Gabion Basket (0.9x2.7 m)	2	$95	$190
	Gabion Basket (0.3x2.7 m)	2	$60	$120
	Geo-textile (meters)	12.2	$1.50	$60
	Rock 3-0s (Mg)	13.6	$22.10	$300
	Rock VDOT #5 (Mg)	4.5	$22.10	$100
	Excavator (hours)	4	$85	$340
	Labor (hours)	42.5	$20	$660
	Dozer (hours)	2	$95*	$190
	Backhoe (hours)	7.5	$65*	$488
BMP- Application Total (including bridge purchase)				**$5,368**
BMP	Labor (hours)	2	$20	$40
	Geo-textile (meters)	30.5	$4.92	$150
	Rock VDOT #5 (Mg)	4.5	$22.10	$100
BMP Additional Application Total				**$290**
BMP Application Total (including BMP-)				**$5,658**
BMP+	Labor	5	$20	$100
	Rock 3-0s (Mg)	4.5	$22.10	$100
BMP+ Application Total				**$200**
Bridge Installation with BMP+ Total Cost				**$5,858**

*Dozer and backhoe costs are hourly rates for local contractors in Patrick County, VA.

2.4.1.2 Culvert Costs

The culvert construction costs totaled $3,568 for the BMP- treatment (Table 4). The addition of Geo-textile and rock added another $597.50 for the BMP treatment for a total BMP treatment cost of $4,165.50. Rip-rap, straw and seed required for the BMP+ treatment added an additional $430, bringing the total BMP+ cost to $,4595.50. Geo-textile was used on the running surface due to the clayey subsoil of the Fairview soil series (Soil Survey Staff, 2014). Soil with less clay and/or more natural rock may not require geo-textile to prevent the gravel from sinking into the running surface. The culvert diameter was necessary for the watershed size and conditions; however, the culvert length could have been reduced if the road vertical alignment and subsequent fill slope ratios had allowed less fill material above the culvert. The reduction of culvert length to 6.1 m (20 feet) would have reduced the initial construction cost by 16% ($565).

Table 4: Crossing and BMP construction materials and costs required for installation of a culvert on a 17 ha watershed.

BMP	Materials	Quantity	Cost/Unit	Total Cost
BMP-	Culvert (6.1 m)	2	$565	$1,130
	Labor (hr)	19.5	$20	$390
	Dozer (hr)	13	$95*	$1,235
	Backhoe (hr)	12.5	$65*	$813
BMP- Application Total (including installation)				**$3,568**
BMP	Labor (hr)	2	$20	$40
	Geo-textile (m)	32	$4.94	$158
	Rock #357 (Mg)	18.1	$22.10	$400
BMP Application Addition Total				**$598**
BMP Application Total				**$4,166**
BMP+	Labor (hr)	5	$20	$100
	Straw (bales)	5	$10	$50
	Seed (22.7 Kg bags)	2	$40	$80
	Rock 3-0s (Mg)	9.1	$22.10	$200
BMP+ Application Total				**$430**
Total Construction plus BMP Cost				**$4,595**

*Dozer and Backhoe costs are hourly rates for local contractors in Patrick County, VA.

2.4.1.3 Ford Costs

The initial Ford construction at BMP- level, required minimal manual labor and equipment and resulted in a cost of only $180 (Table 5). Though this cost was minimal, the ease of travel was not greatly improved, nor did the crossing meet the minimum BMP requirements of the VDOF. The addition of gravel for the BMP level increased cost by $240 providing a total construction cost of $420. This treatment level (BMP) resulted in a crossing that met the minimum VDOF requirements. Due to the soft stream bed the use of Geo-Web and gravel was required to provide a firm running surface through the stream channel. The labor and materials required for Geo-Web installation totaled $1,483 and brought the total cost for the BMP+ treatment to $1,903. This additional cost for Geo-Web would not be required if the stream had a solid bottom.

Table 5: Crossing materials and costs for construction of an improved ford stream crossing using Geo-Web.

BMP	Materials	Quantity	Cost/Unit	Total Cost
BMP-	Labor (hr)	1	$20	$20
	Dozer (hr)	1	$95*	$95
	Backhoe (hr)	1	$65*	$65
BMP- Application Total				**$180**
BMP	Labor	2	$20	$40
	Rock #357 (Mg)	9.0	$22.10	$200
BMP Application Addition Total				**$240**
BMP Application Total				**$420**
BMP+	Labor	21	$20	$420
	Geo-Web (0.15 m x 3.6 m x 4.6 m)	1	$277.90	$278
	Backhoe Hours	9	$65*	$585
	Rock VDOT #5 (Mg)	9.0	$22.10	$200
BMP+ Application Total				**$1,483**
Total Construction plus BMP Cost				**$1,903**

*Dozer and Backhoe costs are hourly rates for local contractors in Patrick County, VA.

2.4.2 Total Suspended Sediment

2.4.2.1 Construction

The construction phase for all three stream crossings increased suspended sediment downstream from the crossing locations; however, the increases varied by two orders of magnitude from the bridge to the two other treatments. Bridge installation produced a total of 0.17 Mg of sediment during the initial construction phase with no increased sediment introduced during the application of additional BMPs (Table 6). Culvert installation resulted in 12.95 Mg of sediment downstream of the crossing. Culvert installation required excavation of the stream channel to set the culvert at the appropriate depth and backfilling over the culvert with soil. The application of rock to the running surface of the road did not impact the stream; however, the application of rip-rap to the fill slopes resulted in an additional 0.03 Mg of sediment. The BMP- and BMP treatments on the ford did not alter the sediment concentration downstream as both the grading of the banks and application of rock to the road surface was completed with the intent to minimize stream channel disturbance. The installation of the Geo-Web required excavation of the stream channel and resulted in an additional 13.04 Mg of sediment.

2.4.2.2 Rainfall Simulation

Rainfall simulations on two of the three crossings indicated sediment loading decreased with increasing BMP level (Table 6). The culvert BMP- treatment produced 3.94 Mg of sediment to the stream channel while the culvert with BMP+ treatment only produced 0.90 Mg during the three 30 minute rainfall simulations. The ford BMP- and BMP+ treatments contributed 5.25 and 1.04 Mg, respectively. The bridge BMP- and BMP+ treatments produced 0.96 and 1.31 Mg, respectively. For both culvert and ford crossings, BMP- (3.94 Mg and 5.25 Mg, respectively) treatment resulted in the greatest total sediment delivery while the BMP+ treatment resulted in the smallest sediment delivery (0.90 Mg and 1.04 Mg for the culvert and ford crossings). Sediment reduction efficiency was calculated by dividing the sediment delivery of a treatment by the treatment with the greatest sediment delivery for each crossing. Sediment reduction efficiency was greatest for culvert and ford BMP+ treatments with 83% and 80%

reductions in sediment delivery when compared to the treatment with the greatest sediment production, ford BMP-.

Although the largest gain was seen by culvert and ford BMP+ treatments, the bridge BMP- treatment reduced sediment by 82% compared to the ford BMP- treatment. The bridge BMP- treatment did result in a greater sediment reduction than the culvert and ford BMP+ treatments and highlights the effectiveness of bridges as a BMP when compared to other stream crossing methods. Although the bridge BMP and BMP+ treatments resulted in negative sediment reduction efficiencies when only investigating the bridge crossing (-20% and -36%, respectively), sediment production was comparable to ford and culvert BMP+ treatments. Increased sediment with increasing BMPs was due, in part, to water and sediment flowing under the bridge surface and into the stream. This unforeseen source of sediment increased sediment levels with increased BMPs. However, the mass of sediment produced was much less than that of the culvert and ford crossings due to the channel disturbance associated with the culvert and ford crossings.

Table 6: Total sediment delivery by crossing and BMP level during rainfall simulations and sediment reduction efficiency by BMP level for each crossing.

		Sediment Delivery (Mg) During Construction and by Rainfall Intensity					Sediment Reduction Efficiency*	
Crossing	**BMP Level**	**Construction Sediment**	**Low Rain**	**Medium Rain**	**High Rain**	**Total Sediment**	**BMPs****	**Crossing x BMP*****
Bridge	BMP-	0.17	0.05	0.35	0.56	0.96	0%	82%
	BMP	0	0.06	0.36	0.74	1.16	-20%	78%
	BMP+	0	0.22	0.28	0.80	1.31	-36%	75%
Culvert	BMP-	12.95	0.39	2.25	1.31	3.94	0%	25%
	BMP	0	0.17	0.31	0.66	1.14	71%	78%
	BMP+	0.03	0.09	0.21	0.60	0.90	77%	83%
Ford	BMP-	0	0.38	1.62	3.25	5.25	0%	0%
	BMP	0	1.37	0.52	1.41	3.31	37%	37%
	BMP+	13.04	0.14	0.37	0.53	1.04	80%	80%

*Sediment reduction efficiency is defined as the ratio between the sediment delivery of a given treatment divided by the treatment with the greatest sediment delivery (i.e. Culvert (BMP-) - Culvert (BMP+) / Culvert (BMP-) = Culvert (BMP+) Sediment Reduction Efficiency).
**BMP Sediment Reduction Efficiency compares each treatment within a crossing type.
*** Crossing x BMP Sediment Reduction Efficiency compares each treatment to the treatment which produced the greatest mass of sediment for all crossings and treatments.

Sediment concentration of each crossing was influenced by the intensity and duration of the rainfall simulation. Sediment concentrations start with low sediment levels at the initiation of rainfall and peak approximately 15 to 30 minutes into the rainfall simulations and again decrease to the baseline levels. Ford and culvert crossings showed a decrease in total sediment delivery with increasing levels of BMPs (i.e. BMP- to BMP to BMP+) while the bridge showed little change through all levels of BMPs (Figure 4).

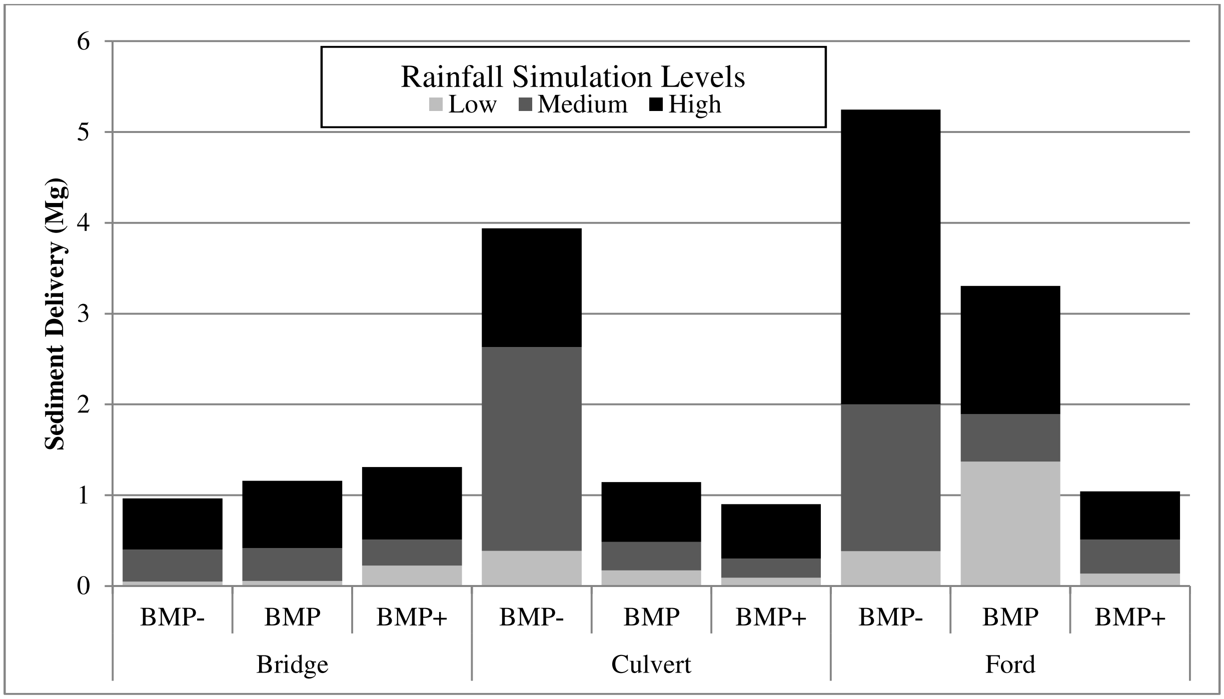

Figure 4: Total sediment delivery (Mg) during the 50 minute period beginning with initiation of the 30 minute rainfall simulation and for 20 minutes after completion of rainfall simulation by crossing and BMP level.

The medium rainfall intensity simulation on the culvert BMP- treatment caused a small pool to develop between the fill slope and the abandoned road. During culvert rainfall simulations the small soil barrier that was holding the pool was overtopped and allowed the small pool to drain directly into the channel, increasing the sediment loading at that point. Visual observations suggested that this increase in sediment concentration was only present during and immediately after the break in the soil barrier. Although the pool was an unforeseen problem with the initial construction and was not a designed portion of the treatment, similar instances may occur for other such crossings.

Since sediment data were not normally distributed log transformations were performed prior to analysis. All crossing and rainfall data were pooled and an analysis of variance of BMP levels was conducted on the pooled data. BMP levels were found to have significant differences ($P<0.001$) with the BMP- treatment producing more sediment than the BMP and BMP+ treatments. A post-hoc Tukey-Kramer HSD test showed the mean sediment delivery per sampling period for the BMP- treatment (0.105 Mg) was significantly different from BMP (0.015 Mg) and BMP+ (0.035 Mg) treatments. This difference of BMP treatments was found while considering all crossings and all rainfall simulation levels.

2.4.3 Sediment Reduction Efficiency

To investigate the benefit-cost relationship between crossing structures, BMPs and sediment reduction, sediment reduction efficiency and associated cost effectiveness ratios were calculated. The sediment reduction value is the difference between the sediment delivery value of the treatment with the largest sediment delivery and the sediment delivery value of the treatment under consideration. The cost effectiveness ratio is provided in US dollars (2014) per Mg of sediment prevented. The values include the total construction and BMP application costs (Table 7). The treatment with the lowest cost effectiveness was the ford BMP treatment, \$124 Mg^{-1} of prevented sediment when compared to the, culvert BMP- treatment. However, comparisons of the cost effectiveness within individual crossings indicated that the lowest cost effectiveness ratio was produced by the ford BMP treatment. The initial construction costs were included in all costs. The difference in cost between the worst treatment and the treatment under consideration was used to calculate the cost effectiveness. For culvert and ford crossings sediment delivery decreased with increased BMPs. However, the bridge with BMP+ resulted in a 0.35 Mg increase in sediment delivery. This increase in sediment delivery resulted in negative sediment reduction and negative cost effectiveness values when only the bridge crossing was investigated. When all crossings were investigated, the bridge BMP and BMP+ treatments showed decreases in sediment compared to the ford BMP-; however the cost effectiveness was several hundred dollars greater than other treatments.

Table 7: Crossing and BMP costs and sediment production with associated cost effectiveness ratio for sediment reduction (US dollars per Mg of sediment prevented).

Crossing and BMP Level Cost and Sediment Production for construction and all levels of rainfall					BMP cost effectiveness by Crossing		Crossing and BMP Efficiency (all crossings/BMP levels)	
Crossing	BMP Level	BMP Cost	Total Cost	Mg	Mg Prevented	$ Mg^{-1}	Mg Prevented	$ Mg^{-1}
Bridge	BMP-	$5,368	$5,368	0.96	-	-	4.28	$1,211
	BMP	$290	$5,658	1.16	-0.19	-$1,495	4.09	$1,340
	BMP+	$200	$5,858	1.31	-0.35	-$1,410	3.94	$1,443
Culvert	BMP-	$3,568	$3,568	3.94	-	-	1.31	$2,590
	BMP	$598	$4,166	1.14	2.79	$214	4.10	$972
	BMP+	$430	$4,596	0.90	3.04	$338	4.34	$1,016
Ford	BMP-	$180	$180	5.25	-	-	-	-
	BMP	$240	$420	3.31	1.94	$124	1.94	$124
	BMP+	$1,483	$1,903	1.04	4.20	$410	4.20	$410

2.5 Discussion

The rainfall simulation allowed for erosion from the stream crossing structure to be separated from erosion that would have originated up-slope of the crossing on the road approach, fulfilling the need for separation of up-slope road approaches and stream crossing structures described by Taylor et al. (1999). Brown et al. (2013) used rainfall simulation in a companion study to evaluated BMP level and sediment delivery from the approaches on the same road as this study and concluded that gravelling either half (BMP level) or the total approach (BMP+) reduced sediment delivery from the approaches by 2-7 fold. Although the sediment from stream crossings was observed without input from the upslope road approach, the areas within the stream crossing structure as defined by Lane and Sheridan (2002) were not distinguishable and sediment that originated on the road surface could not be differentiated from sediment that originated on a fill slope or other area.

Initial construction of the bridge was costly due to increased labor required to prepare abutments and material costs of gabion baskets and geo-textile used due to site specific characteristics. Removal of these items could reduce the material cost by $610 and likely reduce labor by several hours. The bridge material cost after removing gabion baskets is similar to costs reported by McKee et al. (2012) for panel bridges in the Virginia Piedmont ($2,857). However the reported $230 installation cost is approximately 14% of the $1,678 bridge installation cost recorded. This could be due to extra labor required for gabion basket installation as well as cost recording methods by logging contractors in the McKee et al. (2012) survey.

A more likely reason for the differences in costs is because a majority of stream crossings reported by McKee et al. (2012) were for temporary skidder bridges that are simply placed across the stream with a skidder. Our costs are more similar to those reported for permanent roads using a constructed stringer bridge ($7,887) and a three panel wooden bridge ($4,320) reported by Aust et al. (2003). Haul road crossings, even those that use panel bridges, often require more work on abutments and careful placement of panels, so additional costs are expected. Use of onsite equipment may reduce the recorded bridge installation cost if the logger only reported fuel and labor required to install the bridge rather than contractor rates which would include ownership and transportation charges.

The construction phase of culvert with BMP- treatment required channel excavation while the bridge crossing did not require excavation and the ford did not require excavation until the BMP+ treatment. Initial construction and the culvert BMP- treatment produced more sediment than the ford or bridge crossings during initial construction and BMP- treatments.

These findings are similar to the negative downstream water quality impacts from culverts noted by Aust et al. (2011) as well as the decreased downstream sediment from bridge construction, compared to a culvert crossing (Thompson et al., 1995). Geo-Web installation at the ford crossing required excavating the stream bed and resulted in similar sediment delivery as the culvert crossing construction phase, which also required channel excavation. Total sediment production, including construction, was lowest for the bridge, due to the lack of disturbance to the stream channel. Channel excavation during installation of the culvert and upgrade of the ford crossing introduced a large pulse of sediment into the stream. In addition to sediment from channel excavation, increased water velocity downstream of a culvert can have stream scour impacts (Abt et al., 1984) as well as issues for fish passage (Warren and Pardew, 1998).

The bridge crossing showed increases in sediment with increased BMP application. During experiments, visual observations of the stream channel under the bridge panels indicated a large sediment source which entered the stream under the centerline of the bridge behind the gabion baskets. The rock beneath the bridge panel or a soil pipe, which developed while removing stumps, could be responsible for the sediment traveling from the road surface, under the bridge panel and through the gabion. This sediment source may be responsible for increased sediment as BMP levels increased. Sediment entering the channel beneath the bridge panel from the gabion was the only sediment entrance point which was visually observable during the rainfall simulations.

BMPs used in this study were effective at reducing sediment delivery and reinforces the findings of previous BMP studies (e.g. Arthur et al., 1998; Aust and Blinn, 2004; Ice et al., 2010; McKee et al., 2012; Wade et al., 2012; Wear et al., 2013). For all three stream crossings, peak sediment delivery occurred later than the BMP- treatment with increased BMP levels suggesting that they are effective at slowing or reducing overland flow. Altered overland flow could be due to increased surface roughness, depression storage, and changes in infiltration rates. There is evidence that BMPs are effective at reducing stream sedimentation on the culvert and ford crossings when the BMP-, BMP and BMP+ treatments for all crossings were compared. Statistically significant differences were found between the BMP- level and the BMP and BMP+ levels when all crossings were combined. The combined results suggest that the application of BMPs will reduce stream sedimentation and the application of additional BMPs may further reduce stream sediment levels.

Reduction of in-stream sediment with increased BMPs is similar to findings of other studies for skid trail erosion (Sawyers et al., 2012; Wade et al., 2012) and haul road stream crossing approaches (Brown et al., 2013; Brown et al., 2015). However, Wear et al. (2013) found that the greatest level of erosion prevention resulted in increased in-stream suspended sediment when compared to other levels of BMPs on temporary skid trail stream crossings. This difference is likely due to the soil disturbance associated with placement and installation of a silt fence used by Wear et al. (2013) in the steam crossing closeout BMPs. The BMP+ treatment in this study was designed to minimize bare soil and to armor as much disturbed soil as practically possible. Soil disturbance was found to alter the effectiveness of stream crossing approach BMPs (Brown et al., 2015) when the equipment used for the road surfacing BMP treatment left large ruts in the roadway due to muddy conditions. In these cases BMPs were effective unless there was substantial soil disturbance in an area that could drain to the stream channel. A lack of water control structures on a stream approach may increase the volume of water flowing onto and over a crossing structure which could increase soil erosion and possibly sedimentation.

Increased levels of BMPs resulted in decreased sediment delivery on the culvert and ford crossing with the BMP+ treatment resulting in the greatest sediment reduction efficiency. The BMP treatment for the ford resulted in the best BMP cost effectiveness ratio (\$124 Mg^{-1} of sediment reduced), followed by the ford BMP+ treatment (\$410 Mg^{-1} of sediment reduced), and culvert BMP treatment (\$972 Mg^{-1} of sediment reduced). The bridge BMP- treatment resulted in a cost effectiveness (\$1,221 Mg^{-1} of sediment reduced) similar to the culvert BMP+ treatment (\$1,016 Mg^{-1} of sediment reduced) suggesting that the bridge crossing type may be an appropriate BMP for crossing locations in which a bridge can be properly installed. For all three crossings, lower levels of BMPs resulted in decreased costs when compared to BMP+ treatments, however it is unknown if the level of sediment delivery would be considered acceptable.

2.6 Conclusions

Channel disturbances during construction increased downstream sediment concentrations and the only stream crossing treatment that consistently minimized in-stream disturbances was the bridge treatment. The bridge produced the least stream sediment during construction, but it was the most expensive treatment considered in this study. The cost of a bridge may be offset when portable temporary bridges are used. The bridge treatment alone (BMP-) was still a better BMP option than the other stream crossings tested for minimizing in stream sediment concentrations.

Increased levels of BMPs were associated with decreased stream sediment for ford and culvert stream crossings. However, in some cases, increased costs associated with higher level of BMPs for the crossing was growing at a greater rate than the sediment reduction. In situations where funds are limited, it might be more beneficial to target the larger sediment problems first. For example, BMPs applied to the culvert were more beneficial than those applied to the bridge. Each crossing type has unique advantages and disadvantages and downstream sediment can be acceptable below all types of crossings as long as appropriate location and erosion control measures are utilized. Further research that can identify which portions of a crossing structure pose the greatest risk for erosion could further improve cost effectiveness of BMPs by focusing efforts on areas with greatest risk.

Individual site characteristics may warrant installation of one crossing over another. In these cases, landowners and managers must determine which crossing best fits their needs and budget and then apply appropriate BMPs.

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2.7 Literature Cited

Abt S. R., Kloberdanz R. L., Mendoza C. (1984) Unified culvert scour determination. Journal of Hydraulic Engineering 110:1475-1479.

Anderson C., Lockaby B. (2011) Research gaps related to forest management and stream sediment in the United States. Environmental Management 47:303-313.

Arthur M. A., Coltharp G. B., Brown D. L. (1998) Effects of best management practices on forest streamwater quality in eastern Kentucky. Journal of the American Water Resources Association 34:481-495.

Aust W. M., Blinn C. R. (2004) Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years (1982–2002). Water, Air, & Soil Pollution: Focus 4:5-36.

Aust W. M., Carroll M. B., Bolding M. C., Dolloff C. A. (2011) Operational forest stream crossings effects on water quality in the Virginia piedmont. Southern Journal of Applied Forestry 35:123-130.

Aust W. M., Shaffer R. M., Burger J. A. (1996) Benefits and costs of forestry best management practices in virginia. Southern Journal of Applied Forestry 20:23-29.

Aust W. M., Visser R., Gallagher T., Roberts T., Poirot M. (2003) Cost of six different stream crossing options in the Appalachian area. Southern Journal of Applied Forestry 27:66-70.

Beschta R. L. (1978) Long-term patterns of sediment production following road construction and logging in the Oregon coast range. Water Resources Research 14:1011-1016.

Binkley D., Brown T. C. (1993) Forest practices as nonpoint sources of pollution in North America1. JAWRA Journal of the American Water Resources Association 29:729-740.

Boston K. (2012) Impact of the ninth circuit court ruling (Northwest Environmental Defense Center v. Brown) regarding forest roads and the Clean Water Act. Journal of Forestry 110:344-346.

Brown K. R., McGuire K. J., Aust W. M., Hession W. C., Dolloff C. A . (2015) The effect of increasing gravel cover on forest roads for reduced sediment delivery to stream crossings. Hydrological Processes 29:1129-1140.

Brown K. R., Michael Aust W., McGuire K. J. (2013) Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia piedmont. Forest Ecology and Management 310:836-846.

Croke J., Mockler S. (2001) Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. Earth Surface Processes and Landforms 26:205-217.

Croke J., Mockler S., Fogarty P., Takken I. (2005) Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. Geomorphology 68:257-268.

Douglass J. E., Swank W. T. (1972) Streamflow modifications through management of eastern forests. U.S.D.A. Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Eaton A. D., Clesceri L. S., Rice E. W., Greenberg A. E., Franson M. H. (2005) Total suspended solids dried at 103-105 c. Standard methods for the examination of water and wastewater. American Public Health Association, APHA, Washington, DC.

Edwards P. J., Williard K. W. J. (2010) Efficiencies of forestry best management practices for reducing sediment and nutrient losses in the eastern United States. Journal of Forestry 108:245-249.

Fletcher W. A. (2011) Northwest Environmental Defense Center v. Brown. In: No. 07-35266—Unites States Court of Appeals for the Ninth District. 44.

Grace J. M., Rummer B., Stokes B. J., Wilhoit J. (1998) Evaluation of erosion control techniques on forest roads. Transactions of the ASABE 4:383-391.

Ice G. G., Schilling E. G., Vowel J. G. (2010) Trends for forestry best management practices implementation. Journal of Forestry 108:267-273.

Ice G. G., Stuart G. W., Waide J. B., Irland L. C., Ellefson P. V. (1997) Twenty-five years of the Clean Water Act: How clean are forest practices? Journal of Forestry 95:9-13.

Kennedy A.M. (2013) Decker v. Northwest Environmental Defense Center, 133 S. Ct. 1326, 568 U.S., 185 L. Ed. 2d 447. Supreme Court of the United States.

Kochenderfer J. N. (1970) Erosion control on logging roads in the appalachians. Research Paper, NE-158. U.S.D.A. Forest Service.

Kochenderfer J. N., Helvey J. D. (1987) Using gravel to reduce soil losses from minimum-standard forest roads. Journal of Soil and Water Conservation 42:46-50.

Lakel W. A., Aust W. M., Bolding M. C., Dolloff C. A., Keyser P., Feldt R. (2010) Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. Forest Science 56:541-551.

Lakel W. A., Poirot M. (2013) Silvicultural best management practices implementation monitoring for virginia, 2012. Virginia Department of Forestry, Charlottseville, VA.

Lane P. N. J., Sheridan G. J .(2002) Impact of an unsealed forest road stream crossing: Water quality and sediment sources. Hydrological Processes 16:2599-2612.

Lim S. Y. (1995) Scour below unsubmerged full-flowing culvert outlets. Proceedings of the ICE - Water Maritime and Energy 112:136-149.

McKee S. E., Shenk L. A., Bolding M. C., Aust W. M. (2012) Stream crossing methods, costs, and closure best management practices for Virginia loggers. Southern Journal of Applied Forestry 36:33-37.

Megahan W. F.(1972) Logging, erosion, sedimentation--are they dirty words? Journal of Forestry 70:403-407.

Megahan W. F., Wilson M., Monsen S. B. (2001) Sediment production from granitic cutslopes on forest roads in Idaho, USA. Earth Surface Processes and Landforms 26:153-163.

Mendoza C., Abt S. R., Ruff J. F. (1983) Headwall influence on scour at culvert outlets. Journal of Hydraulic Engineering 109:1056-1060.

Moore R. (2004) Introduction to salt dilution gauging for streamflow measurement: Part 1. Streamline Watershed Management Bulletin 7:20-23.

Moore R. D. D. (2005) Slug injection using salt in solution. Streamline Watershed Management Bulletin 8:1-6.

Patric J. H. (1976) Soil erosion in the eastern forest. Journal of Forestry 74:671-677.

Peirce J. J. (1980) Strategies to control nonpoint source water pollution. Journal of the American Water Resources Association 16:220-225.

Pimentel D., Harvey C., Resosudarmo P., Sinclair K., Kurz D., McNair M., Blair R. (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117-1123.

Reid L. M., Dunne T. (1984) Sediment production from forest road surfaces. Water Resources Research 20:1753-1761.

Rothwell R. L. (1983) Erosion and sediment control at road-stream crossings. The Forestry Chronicle 59:62-66.

Sawyers B. C., Bolding M. C., Aust W. M., Lakel W. A. (2012) Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia piedmont. Journal of Soil and Water Conservation 67:300-310.

Sheridan G. J., Noske P. J. (2007) A quantitative study of sediment delivery and stream pollution from different forest road types. Hydrological Processes 21:387-398.

Surfleet C. G. (2011) Road runoff and sediment sampling for determining road sediment yield at the watershed scale. Canadian Journal of Forest Research 41:1970-1980.

Swift L. W. (1984) Gravel and grass surfacing reduces soil loss from mountain roads. Forest Science 30:657-670.

Taylor S. E., Rummer R. B., Yoo K. H., Welch R. A., Thompson J. D. (1999) What we know -- and don't know -- about water quality at stream crossings. Journal of Forestry 97:12-17.

Thompson J. D., Taylor S. E., Yoo K. H., Brinker R., Tufts R. A. (1995) Water quality impacts from different road stream crossings. Presented at the Council on Forest Engineering - Sustainability, Forest Health and Meeting the Nations Needs For Wood Products, (1995) Corvallis, OR.

Trimble G. R., Sartz R. S. (1957) How far from a stream should a logging road be located? Journal of Forestry 55:339-341.

Ursic S. J. (1991) Hydrologic effects of clearcutting and stripcutting loblolly pine in the coastal plain. Journal of the American Water Resources Association 27:925-937.

Virginia Department of Forestry. (2009) Virginia's forestry best management practices for water quality.Virginia Department of Forestry, Charlottesville, VA.

Visser R., Aust W. M., Gallagher T., Roberts T., Poirot M. (2003) Cost of six different stream crossing options in the Appalachian area. Southern Journal of Applied Forestry 27:66-70.

Wade C. R., Bolding M. C., Aust W. M., Lakel W. A. (2012) Comparison of five erosion control techniques for bladed skid trails in Virginia. Southern Journal of Applied Forestry 36:191-197.

Warren M. L., Pardew M. G. (1998) Road crossings as barriers to small-stream fish movement. Transactions of the American Fisheries Society 127:637-644.

Wear L. R., Aust W. M., Bolding M. C., Strahm B. D., Dolloff C. A. (2013) Effectiveness of best management practices for sediment reduction at operational forest stream crossings. Forest Ecology and Management 289:551-561.

Yoho N. S. (1980) Forest management and sediment production in the south - a review. Southern Journal of Applied Forestry 4:27-36.

Zar J. H. Biostatistical analysis, fourth edition. (1999) Upper Saddle River, New Jersey 07458: Prentice Hall.

3.0 Sedimentation Following Legacy Forest Road Stream Crossing Improvement and Best Management Practice Installation

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Keywords: Best Management Practices, stream crossings, sediment, erosion

3.1 Abstract

Legacy forest haul road stream crossings are often used in the Piedmont region of the southeastern United States. These crossings typically consist of unimproved fords with minimal erosion control measures that need improvement prior to use for forest operations. Currently, the water quality and cost impact of replacing legacy fords with appropriate crossing structures and best management practices is not well documented. To determine impacts of crossing improvement, stream suspended sediment levels were monitored daily above and below three legacy fords for nine months before and six months after construction of an improved ford, bridge, and culvert. The three crossings were constructed with best management practices exceeding state recommendations. All three crossings showed a reduction in mean daily Δ sediment concentration (g mL^{-1}). The bridge (0.004 g L^{-1} pre-construction and -0.010 g L^{-1} post construction) (P=0.0096) and culvert (0.0.038 g L^{-1} pre-construction and -0.004 g L^{-1} post construction) ($P<0.0001$) resulted in a statistically significant ($p<0.05$) sediment reduction while the ford did not (0.048 g L^{-1} pre-construction and 0.021 g L^{-1} post construction) (P=0.8489). The bridge and culvert crossing improvements resulted in a statistically significant ($p<0.05$) decrease in stream sediment while the ford crossing did not result in a significant change in sediment.

3.2 Introduction

Forest roads were recognized early on as having potential impact on water quality in streams on both eastern and western forests in the United States (e.g. Anderson, 1954; Trimble and Sartz, 1957; Haupt, 1959). Stream sediment from forest operations is currently treated as a non-point source pollutant (NPSP) in the United States; however, timber harvesting has been shown to increase sediment levels (Binkley and Brown, 1993). In the southeastern United States, roads that were developed prior to the implementation of best management practices (BMPs) are of particular concern due standards that were inadequate in protecting water quality. Many of these "legacy" roads were developed during agricultural land use periods and continue to be used to access forest land. Brown et al. (2013) found that the implementation of current BMPs on unimproved and un-designed forest roads at stream crossings can reduce erosion and thus stream sedimentation rates. However, Brown et al. (2013) only investigated implementing BMPs on the road approach to the stream crossing which did not include the crossing structures themselves.

States developed BMPs in 1972 after the passing of the Federal Water Pollution Control Act. The BMPs have been found to be effective in reducing erosion and sedimentation from forest operations (e.g. Arthur et al., 1998; Aust and Blinn, 2004; Ice et al., 2010; McKee et al., 2012; Wade et al., 2012). Though BMPs have been proven effective their overall impact on water quality is not fully understood due to a lack of in stream water quality criteria or standards (Peirce, 1980; Corner et al., 1996). BMPs are in continuous need of updating and development that is based upon current research (Ice et al., 1997).

3.2.1 Stream Crossings

Stream crossings can be a major sediment source in forested streams, but studies investigating the impact of various types of crossings are limited in both number and scope (Taylor et al., 1999). Limitations in scope are due to a lack of information regarding the sediment loading to the stream during crossing installation, quantification of sediment from different types of crossings, and separation of the sediment production from the crossing structure from that of the road approach (Taylor et al., 1999).

Stream crossings and associated BMPs have been identified as an area of concern for potential erosion and sediment delivery from forest harvesting operations in Virginia (Lakel and Poirot, 2013). A 2009 survey of loggers in the Virginia Piedmont showed that 48% of loggers had installed a haul road stream crossing in the preceding 12 months with 8%, 20%, 12%, and 20% of the crossings as fords, culverts, wooden bridges, and steel bridges, respectively (McKee et al., 2012). The use of culvert pipes allows for traffic to pass without contacting the stream bed or water, thereby reducing direct input of sediment from traffic. However, the use of culverts has been shown to result in channel scour at the outlet (Mendoza et al., 1983; Lim, 1995). Aust et al. (2011) found that bridges minimized impacts on water quality. Bridges allow for vehicles to pass without contact with stream water, similar to a properly installed culvert. Bridge crossings also require less stream channel and bed modification during installation and removal. Installation of a culvert crossing was tested using rainfall simulation and the resulting total suspended sediment and turbidity increased two to three times above the baseline sediment and turbidity values (Lane and Sheridan, 2002).

Surface cover of soil disturbed during crossing construction activities has been shown to reduce erosion rates. However the use of grass seeding requires germination, thus erosion rates are reduced as the seed germinates and becomes established (Rothwell, 1983; Lane and Sheridan, 2002). Beyond establishment of vegetation, erosion has been found to decrease with time following construction activities as easily eroded material is quickly displaced leaving more resilient soil particles (Megahan et al., 2001). Rainfall simulation experiments have identified factors leading to erosion on stream crossings (Lane and Sheridan, 2002) and road approaches (Brown et al., 2015) during and emediatly following construction and road maintenance periods. Studies investigating impacts of individual crossings in the Virginia Piedmont have recently been conducted; however, they have focused on temporary skid trail crossings (Wear et al., 2013) or haul road crossings with minimal pre and post crossing installation monitoring (Aust et al., 2011).

Rainfall simulation (Lane and Sheridan, 2002) and short term water quality monitoring of skid trail (Wear et al., 2013) and haul road stream crossings (Aust et al., 2011) have provided investigations of erosion and sedimentation potential of stream crossings immediately following construction. Watershed scale studies have also been conducted to investigate long term stream sediment impacts of forest harvesting and road building activities (Kochenderfer, 1970; Ursic and Douglass, 1978; Ursic, 1991). However, the long term impact of upgrading an unimproved legacy ford stream crossing with an appropriate crossing structure utilizing BMPs beyond state recommendations has not been tested with regard to sediment. Due to the lack of understanding of the long term impact of these crossing improvements, it is unclear if upgrading these crossings results in a long term reduction in stream sediment.

3.2.2 Objectives

This study was designed to evaluate changes in stream sediment over a 15 month period resulting from the upgrade of three legacy forest road stream crossings and installing appropriate best management practices. Specific objectives were to 1) quantify daily sediment concentrations from existing, unimproved legacy ford stream crossings, 2) determine the daily sediment concentrations of improved stream crossings with appropriate best management practices, and 3) evaluate differences in stream sediment following treatment installations.

3.3 Materials and Methods

3.3.1 Site Description

Data collection was conducted in the Piedmont physiographic region of Virginia at the Reynolds Homestead Forest Resources Research Center in Patrick County, VA (36°38'N 80°8'W). Forest management and harvesting in the area includes loblolly pine (*Pinus taeda*) plantations, natural Virginia pine stands (*Pinus virginiana*), and mature mixed hardwood forests. At the site, stream crossings along a legacy road (>100 years old) with minimal BMPs were improved on three perennial streams (Figure 5). The legacy road is used as an access road for forest operations as well as teaching and research activities. The three crossings were identified and the most appropriate crossing type was chosen based upon crossing characteristics including road approach elevation, stream alignment, and stream width. The watershed area above each crossing consists of mixed hardwood forest cover and ranged from 17.0 to 40.4 ha in size. Stream slope was approximately 2% for all three streams and sand and gravel made up the largest portions of bed material (Table 8).

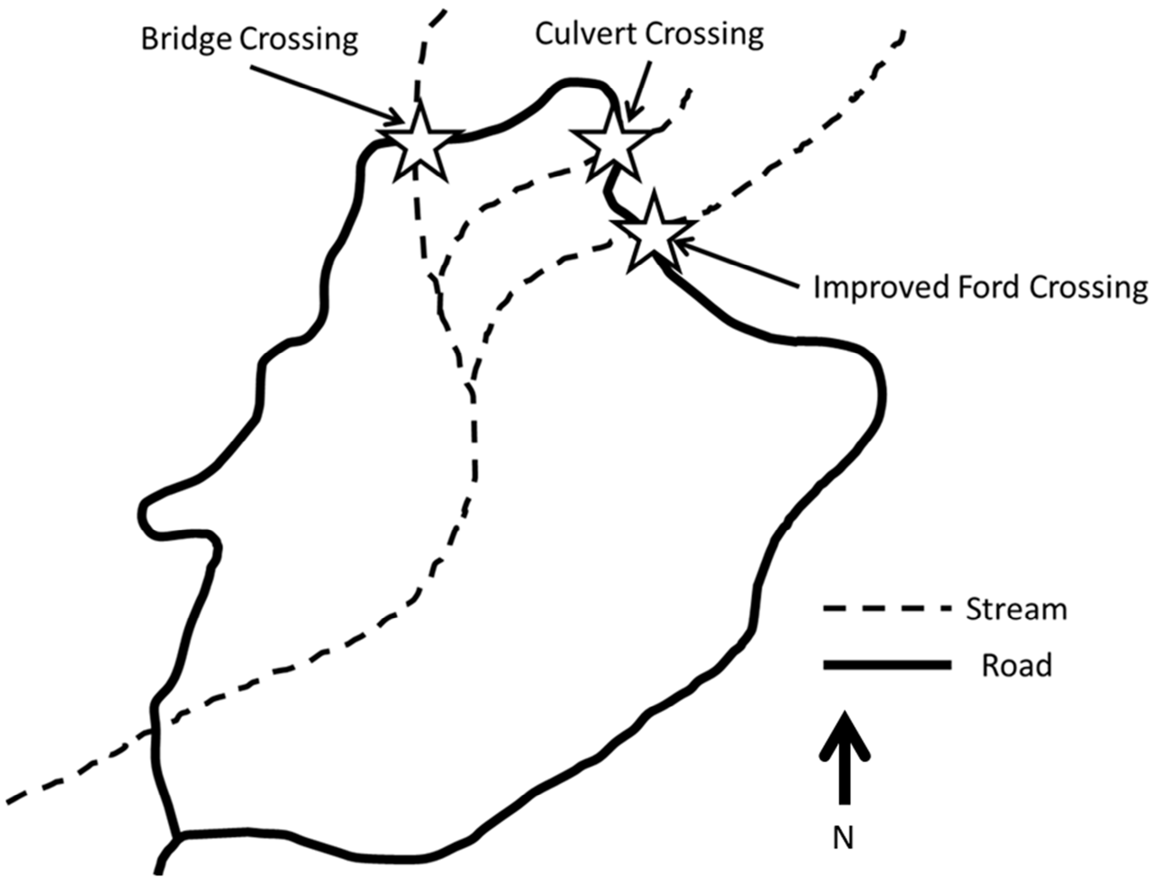

Figure 5: The legacy forest road crosses three separate streams above the stream confluence and again below the confluence of the three streams. Original stream crossings for the bridge, culvert and ford crossings were unimproved legacy ford stream crossings. The fourth stream crossing (below stream confluence) was upgraded with a concrete and culvert pipe low water crossing prior to this project. (Not to scale)

Table 8: Stream characteristics and watershed area are shown for each installed crossing. Watershed area is measured from crossing location. Stream slope, full bank width and depth measured immediately upstream of installed crossing location. Bed load composition is based upon a 40 sample bed material survey.

					Bed Material (%)				
Crossing	Watershed Area (ha)	Stream Slope (%)	Full Bank Width (m)	Depth at Full Bank (m)	Silt/Clay (%)	Sand (%)	Gravel (%)	Cobble (%)	Boulder (%)
Bridge	40.4	2	2.65	0.28	10.0	27.5	45.0	17.5	0.0
Culvert	17.0	2	2.29	0.16	7.5	25.0	42.5	25.0	0.0
Ford	32.4	2	3.41	0.26	7.3	19.5	46.3	19.5	7.3

3.3.2 Crossing Installations

The bridge is comprised of 3 white oak (*Quercus alba*) panels that are 7.3 m long, 1.2 m wide, and 0.2 m thick. The panels were combined to form a bridge 7.3 m long and 3.6 m wide with a span of 2.8 m. The eastern abutment utilized two gabion baskets (0.9 m x 0.9 m x 3.6 m) that were placed along the edge of the stream channel. The gabion baskets were filled with #3-0 (7 - 15 cm) stone. Approximately 0.6 m of fill was required behind the gabion baskets to obtain the desired grade on the bridge approach. Geo-textile was applied on both stream banks where the bridge panels were to rest. Approximately 5 cm of VDOT #5 (1.25 - 5 cm stone) drain rock was applied on the geotextile to allow for water to drain away from the bridge panels and increase the longevity of the permanent bridge. BMPs utilized on the bridge crossing included applying geo-textile and VDOT #5 rock to the road running surface as well as applying rip-rap (10 – 30 cm stone) to the fill slopes and other areas of disturbed soil.

For the culvert crossing the Virginia Department of Forestry BMP manual (VDOF, 2009) specified a 0.9 m (36 inch) culvert for the 17 ha watershed. Two 6.1 m (20 foot) culverts were combined to create a 12.2 m (40 foot) pipe to achieve desired road alignment with adequate fill above the culvert. BMPs utilized on the culvert crossing included geo-textile and #357 gravel (approximately 1-5 cm stone) on the running surface and straw mulch, grass seed and rip-rap on the fill slopes.

The ford crossing stream bed was reinforced utilizing Geo-Web to stabilize the Virginia Department of Forestry specified VDOT #5 gravel which was placed in the stream channel. The Geo-Web is 15.2 cm in depth and covers an area approximately 3.6 m wide and 4.6 m in length. In addition to the Geo-Web stream bed stabilization the road approaches were graveled with #357 gravel and bare soil was covered with native stone.

3.3.3 Stream Measurements

Total suspended solids (TSS) samples were collected 20 m upstream and 20 m downstream of each crossing beginning in February, 2012 and continued during the construction phase (1-5 days per crossing) and ended in March of 2013 using ISCO 3700 automatic water samplers. Five-hundred mL samples were taken daily at noon and were collected for transport to the laboratory every 14 days. After collection, samples were stored at 4°C for no more than 1 week prior to processing. The analytical procedure followed the methods for total suspended solids dried at 103-105°C outlined by the American Public Health Association (Eaton et al., 2005). Samples were vacuum filtered through pre-weighed 1.5 micron fiberglass filters. Filters with sediment were dried for 24 hours at 105°C before being weighed. TSS concentration was calculated by subtracting the mass of the oven dried sediment and filter from the filter tare mass and dividing by the volume of water filtered. The difference between the downstream sediment concentration and upstream sediment concentration was used to calculate the change in sediment contribution within the reach of stream occupied by the crossing structure.

Analysis of pre and post improvement conditions was conducted with the SAS JMP Pro 10 statistical software package (JMP, 2009). The time series of daily sediment samples required methods to address the lack of independence between daily samples. Two time series analysis methods were utilized to address the lack of independence. The first method employed a 15 day lag correlation utilizing the lag function in JMP. The 15 day lag was chosen due to the 14 day sampling period used during field sample collection and associated autocorrelation. The lag function provides a shift in the data at the specified value and can reduce autocorrelation within a time series. The sample collection process also included maintenance to the sampling system which included cleaning of the in stream water intake. The lag adjusted data were then analyzed using a Wilcoxon/Kruskal-Wallis median comparison of pre- and post-construction time periods. The second method utilized the Auto Regressive Integrated Moving Average (ARIMA) model. Model residuals were compared using a Student's T test of the pre- and post-construction time period. A significant difference in the residuals between time periods suggests that the original data is from different populations.

Water samples were collected for 15 months from January, 2011 until removal of the ISCO water samplers in March, 2013. The equipment was installed and maintained for approximately nine months of monitoring prior to crossing improvement and another six months post improvement. However, due to occasional failures of either the upstream or downstream water samplers the data record is not a consecutive nine months. In order for a data point to be valid on a given day, both above and below crossing samples had to be collected. The failures resulted in approximately 100 days prior to construction and 140 days post construction with reliable data. The two statistical methods were utilized due to the implications of non-consecutive data on an ARIMA model and autocorrelation concerns with lag adjusted data.

3.4 Results

The daily rainfall was obtained from the NRCS-SCAN weather station located <1000 m from the stream crossings (NRCS, 2013). Mean daily rainfall in the pre- and post-construction time periods were tested for significant difference using a paired T-Test (α=0.05) for each crossing. The dates of construction for the study ranged from July 2012 to October 2012. Due to the differences in improvement dates and thus different pre- and post-construction time periods, daily rainfall was tested separately for each crossing. For all three crossings, rainfall was found to lack statistically significant differences in means between the pre and post improvement phases. The lack of significant differences between pre and post installation rainfall allows for a direct comparison of Δ sediment concentration (g mL^{-1}) (Table 9).

Analysis of time lag adjusted data suggests significant differences between the mean Δ sediment concentration of the culvert and bridge crossing; however, the ford did not show a significant difference in mean sediment concentration. Though the time lag adjustment of the data accounts for the lack of independence of daily sediment samples, it only accounts for a 15 day time period and thus may not account for ongoing changes to the stream channel that may or may not be associated with crossing construction. To account for stream channel changes an ARIMA model was used to predict sediment values based upon the time series data. A model was developed for each crossing covering the entire data collection time frame. ARIMA models produced R^2 values of 0.426, 0.353 and 0.394 for the bridge, culvert and ford crossings (Table 10).

Table 9: Descriptive statistics for Δ Sediment Concentration (g L-1) (downstream sediment concentration – upstream sediment concentration) for all three crossings (Bridge, Culvert and Ford) pre and post crossing installation. Median lag (15) values and associated Wilcoxon/Kruskal-Wallis median test P-values for all three crossings showing significant differences in pre and post installation sediment values.

	Δ Sediment Concentration ($g\ L^{-1}$)			Lag (15) of Δ Sediment Concentration	
Crossing and Construction Phase	min	median	max	median	P-Value
Bridge Pre	-0.048	-0.003	0.047	-0.0012	0.0096
Bridge Post	-0.114	-0.007	0.246	-0.0044	
Culvert Pre	-0.332	0.021	0.517	0.0320	<0.0001
Culvert Post	-0.186	-0.006	0.342	0.0002	
Ford Pre	-0.160	0.021	0.178	0.0136	0.8489
Ford Post	-0.063	0.009	0.231	0.0182	

Table 10: Auto Regressive Integrated Moving Average (ARIMA) (Order 1) model parameter estimates by crossing type.

	ARIMA Parameter Estimates						
Crossing	Term	Lag	Estimate	t Ratio	P-value	Constant	R^2
Bridge	AR	1	0.6531	16.06	<0.0001	0.0025	0.426
	Intercept	0	0.0072	0.74	0.4609		
Culvert	AR	1	0.605	14.28	<0.0001	0.0129	0.353
	Intercept	0	0.0306	3.28	0.0011		
Ford	AR	1	0.6394	14.29	<0.0001	0.0154	0.394
	Intercept	0	0.0427	5.6	<0.0001		

The pooled t-test suggests that there is no difference in stream sediment levels between the pre and post construction time periods for the bridge and ford crossings. However, the culvert crossing construction resulted in decreased sediment levels (Table 11).

Table 11: Pooled t-test results showing differences in ARIMA residual means between pre and post construction time periods.

Residual Pooled t-Test		
Construction Phase	Mean Residual	P-Value
Bridge Pre Construction	-0.0011	0.8142
Bridge Post Construction	0.0006	
Culvert Pre Construction	0.0097	0.0141
Culvert Post Construction	-0.0099	
Ford Pre Construction	-0.0034	0.2958
Ford Post Construction	0.0030	

The Wilcoxon/Kruskal-Wallis test of median lag values and the pooled t-test of ARIMA residuals suggest that the culvert crossing improvement resulted in decreased sediment post construction. The significant difference of the culvert residuals indicates that the pre- and post-construction sediment data were from different populations. In addition, the ford crossing did not show a significant difference in either test; however, the bridge crossing construction resulted in a significant difference in the lag median testing, but not in the ARIMA residual analysis.

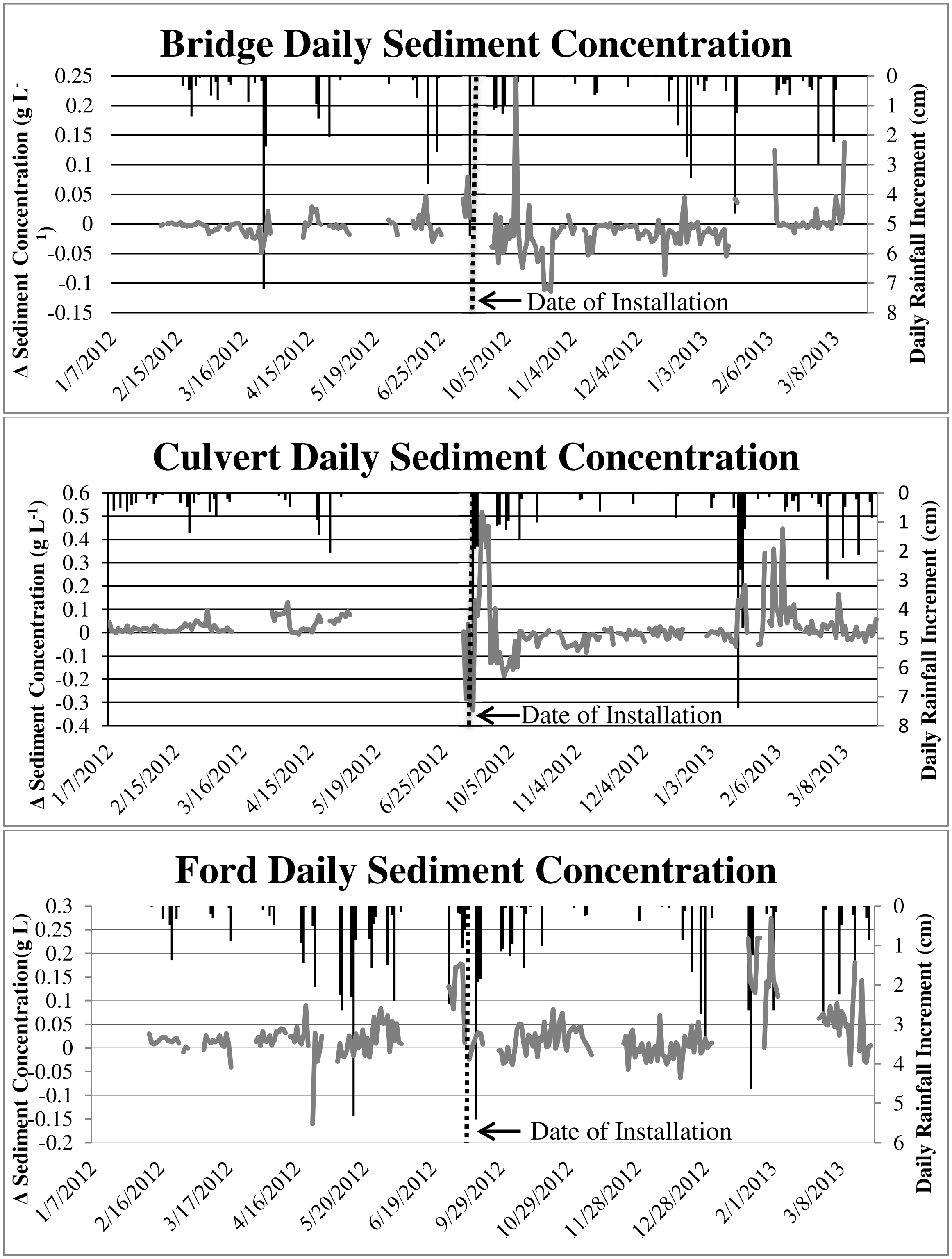

Figure 6: Bridge (top), Culvert (middle), and Ford (bottom) crossing daily Δ sediment concentration (g mL^{-1}) and rainfall (mm day^{-1}) calculated as downstream TSS – upstream TSS.

The bridge crossing showed a Δ sediment concentration near the zero line prior to the crossing installation (Figure 6). On March 25, 2012 the Δ sediment concentration showed minimal response to a >70 mm rain event. Following the bridge installation Δ sediment concentration showed a mean and median level less than the pre installation period. The mean and median were both below zero in the post improvement time period. The difference between the pre and post installation phases for the culvert crossing was found to be statistically significant ($p<0.0001$). The mean and median sediment concentrations decreased in the post improvement time period. In early January 2013 and into February 2013 there were several larger rain storms (>4 cm day^{-1}). These storms resulted in increased sediment levels. The increased sediment levels following these rain events may be due to natural variability in the system or the minimal time since disturbance. The ford treatment did not show a statistically significant difference in Δ sediment concentration. Following crossing improvement, the sediment levels decreased; however, storm events greatly increased sediment (Figure 8).

The bridge and culvert crossings both showed a significant decrease in sediment following the crossing improvement. Both crossings received increased levels of BMP protection, altered road approaches and structures which decreased the sediment impact from vehicles entering the stream. Though many BMPs were applied, the connection between the approaches and the stream was retained. The old approaches for the bridge crossing were not decommissioned and thus the potential flow routing on the approach was not changed. The culvert crossing on the other hand has a stream channel that was severely altered and the construction of the culvert required decommissioning of the legacy approaches and thus reducing the connectivity of the legacy road with the stream.

Further analysis of stream sediment is based upon separating storm events into three levels of daily rainfall. Rainfall values were monitored throughout the sample period. Rainfall was categorized into three categories: “None”, no rainfall; “Low”, rainfall <3.3 mm (median rainfall when days with zero rainfall were removed); and, “High”, rainfall >3.3 mm. The categorization of rainfall allowed for equal comparisons between pre and post construction time periods due to a lack of significant difference between the rainfall values in the two time periods.

The differences in sediment concentration by installation phase were tested for each crossing structure by rainfall category. At high rainfall the sediment concentration showed no statistical difference for the bridge, culvert, and ford crossings ($p>0.5$). At low rainfall statistically significant differences in sediment concentration for the culvert and ford crossings and a marginally significant difference for the bridge crossing, $p=0<0.01$, 0.05, and 0.10, respectively. The sediment concentration when no daily rainfall was recorded showed statistically significant differences for the bridge and culvert crossing structures (bridge $p<0.01$, culvert $p=0.02$) while the ford showed a lack of statistical significance ($p>0.5$). All three crossings showed similar results when rainfall was blocked into categories as when rainfall was combined. The difference when no rainfall is present suggests that during base flow conditions the new crossing structures result in decreased sedimentation, likely due to a decrease in stream bed disturbance associated with eliminating traffic from entering the stream channel and sediment trapping.

3.5 Discussion

All three crossings had similar mean daily rainfall in the pre and post installation time periods ($p>0.4$). This lack of difference allowed for a direct comparison of the pre and post installation sediment concentration (g L^{-1}). Prior to construction, all three unimproved legacy ford stream crossings had low standards, steep approaches, and inadequate water control structures. The pre installation crossings had settled over time and due to processes illustrated by Megahan et al. (2001) likely showed decreased erosion rates due to the time since disturbance. Brown et al. (2013) listed these characteristics as factors which result in greater levels of erosion and thus stream sedimentation. All three crossings showed a reduction in mean and median sediment loading, though not all were significant. All three crossings had minimal erosion control on the road approaches prior to construction and thus the reductions in sediment may be attributed to the application of gravel and grass seeding on the crossing approaches as was documented in previous studies (Swift, 1984; Kochenderfer and Helvey, 1987; Brown et al., 2013; Brown et al., 2015). The reduction in sediment levels observed at the culvert and ford crossings supports the findings of other studies which found that BMPs are effective at reducing erosion and sediment (Briggs, 1998; Wynn et al., 2000; Aust and Blinn, 2004; Shepard, 2006).

Both statistical tests compared central values (means and medians) and may not capture biologic or hydrologic impacts from single large events. Though there is a statistically significant difference in means for the culvert (lag and ARIMA models) and bridge (lag model) crossings, the range of sediment contribution as well as the impacts of a few large storm events raises concerns about statistical analysis of before-after intervention data mentioned by Murtaugh (2002). The means may be altered by influential data points surrounding storm events, though these data points are not common, they may be the most important in terms of biological impacts of sediment.

All three crossing structures required realignment of the road approach and thus the connectivity of the road network to the channel was altered. For both the culvert and bridge the connectivity was likely decreased due to the road approach no longer directly entering the channel as is seen in a ford crossing. The bridge and culvert both provide an area for water draining from the road surface to decrease velocity in either a vegetated buffer strip, such as the slopes leading from the road fill to the stream near a bridge, or a rock armored slope, such as a culvert fill slope. Decreased connectivity may result in decreased sediment contribution from the road approach between the stream crossing and the nearest water control structure. Further, both the bridge and culvert crossings no longer require vehicles to travel through the stream channel. Even with the improved ford crossing vehicles must still drive directly through the channel. Though the channel is stabilized, which reduces stream bed disturbance and improves the ease of travel on the road, the vehicle must still pass its tires through the channel. In addition to vehicles traveling through the stream channel, the road approach directly enters the stream on the ford crossing and thus any material which is eroded in the 5 to 10 m above the channel will have direct connectivity to the channel, where a bridge or culvert crossing would have a buffer area for the water and eroded material to settle prior to entering the channel.

There is no direct comparison between the crossing structures. Each structure was chosen for the stream it was installed on due to the characteristics of the road and stream. For each individual stream crossing location, land managers must determine the best crossing structure that fits their needs in terms of traffic and financial requirements as well as the characteristics of the road and stream. In the case of the treatments tested, the bridge crossing was installed rather than a ford due to the relatively tall stream banks (approximately 1m) at the crossing location. At the same time, a culvert would not have been appropriate where the ford was installed due to the lack of needed elevation in the road surface to clear the appropriate sized culvert.

3.6 Conclusions

The replacement of legacy ford stream crossings, which had little to no erosion control measures with designed stream crossings that exceed the current stream crossing BMP requirements, showed mixed results. For the culvert and bridge crossings the mean daily sediment contribution was decreased after replacing the legacy crossing with a structure with increased erosion mitigation measures. However, the installation of an improved ford stream crossing did not result in a statistically significant difference in sediment contribution. Both the bridge and culvert crossings reduced the sediment delivery ratio between the road approach and stream channel by providing a buffer area which is able to decrease overland flow and allows for the deposition of eroded material from the road surface prior to entering the stream. If the legacy road approaches had been completely abandoned and rehabilitated, it may have altered the post construction sediment contribution. The ford crossing retained the hydrologic connection between the road approach and the stream channel with no buffer strip as the road approach directly enters the stream crossing. Though the ford did not result in statistical difference in sediment contribution, vehicles traveling the road were able to negotiate the new crossing with greater ease and the Geo-web and rock in the stream bed likely decreased the amount of in stream sediment that was disturbed during times of traffic. Though traffic patterns on the roads were similar pre and post installation periods, the frequency of traffic was not great enough to allow for a robust traffic impact analysis. Though the construction of the new crossings had mixed results in terms of sediment contribution, the new crossings allowed for easier traveling of the road in all conditions.

3.7 Literature Cited

Anderson H.W. (1954) Suspended sediment discharge as related to streamflow, topography, soil, and land use. Eos, Transactions American Geophysical Union 35(2): 268-281.

Arthur M. A., Coltharp G. B., Brown D. L. (1998) Effects of best management practices on forest streamwater quality in eastern Kentucky. Journal of the American Water Resources Association 34:481-495.

Aust W. M., Blinn C. R. (2004) Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years. Journal of Water, Air and Soil Pollution 4:32-36.

Aust W. M., Carroll M. B., Bolding M. C., Dolloff C. A. (2011) Operational forest stream crossings effects on water quality in the Virginia piedmont. Southern Journal of Applied Forestry 35:123-130.

Binkley D., Brown T. C. (1993) Forest practices as nonpoint sources of pollution in North America. Journal of the American Water Resources Association 29:729-740.

Briggs R. D. (1998) Compliance with forestry best management practices in Maine. Northern Journal of Applied Forestry 15:57-68.

Brown K. R., McGuire K. J., Aust W. M., Hession W. C., Dolloff C. A. (2015) The effect of increasing gravel cover on forest roads for reduced sediment delivery to stream crossings. Hydrological Processes 29:1129-1140.

Brown K. R., Aust W. M., McGuire K. J. (2013) Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia piedmont. Forest Ecology and Management 310:836-846.

Corner R. A., Bassman J. H., Moore B. C. (1996) Monitoring timber harvest impacts on stream sedimentation: Instream vs. Upslope methods. Western Journal of Applied Forestry 11:25-32.

Eaton A. D., Clesceri L. S., Rice E. W., Greenberg A. E., Franson M. H. (2005) Total suspended solids dried at 103-105 c. Standard methods for the examination of water and wastewater. American Public Health Association, APHA, Washington, DC.

Haupt H.G. (1959) Road and slope characteristics affecting sediment movement from logging roads. Journal of Forestery 57(5): 329-332.

Ice G. G., Schilling E. G., Vowel J. G. (2010) Trends for forestry best management practices implementation. Journal of Forestry 108:267-273.

Ice G. G., Stuart G. W., Waide J. B., Irland L. C., Ellefson P. V. (1997) Twenty-five years of the Clean Water Act: How clean are forest practices? Journal of Forestry 95:9-13.

JMP®, Version 9.0.0. SAS Institute., Cary, NC, 1989-2007

Kochenderfer J. N.(1970) Erosion control on logging roads in the Appalachians. Research Paper, NE-158. U.S.D.A. Forest Service.

Kochenderfer J. N., Helvey J. D. (1987) Using gravel to reduce soil losses from minimum-standard forest roads. Journal of Soil and Water Conservation 42:46-50.

Lakel W. A., Poirot M. (2013) Silvicultural best management practices implementation monitoring for Virginia, 2012. Virginia Department of Forestry, Charlottseville, VA.

Lane P. N. J., Sheridan G. J. (2002) Impact of an unsealed forest road stream crossing: Water quality and sediment sources. Hydrological Processes 16:2599-2612.

Lim S. Y. (1995) Scour below unsubmerged full-flowing culvert outlets. Proceedings of the ICE - Water Maritime and Energy 112:136-149.

McKee S. E., Shenk L. A., Bolding M. C., Aust W. M. (2012) Stream crossing methods, costs, and closure best management practices for Virginia loggers. Southern Journal of Applied Forestry 36:33-37.

Megahan W. F., Wilson M., Monsen S. B. (2001) Sediment production from granitic cutslopes on forest roads in Idaho, USA. Earth Surface Processes and Landforms 26:153-163.

Mendoza C., Abt S. R., Ruff J. F. (1983) Headwall influence on scour at culvert outlets. Journal of Hydraulic Engineering 109:1056-1060.

Murtaugh P. A. (2002) On rejection rates of paired intervention analysis. Ecology 83:1752-1761.

Natural Resource Conservation Service Staff (NRCS). Soil Climate Analysis Network. National Water and Climate Center (NWCC). Site 2089. Available online at http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=2089&state=va/. Accessed November 14, 2013.

Peirce J. J. (1980) Strategies to control nonpoint source water pollution. Journal of the American Water Resources Association 16:220-225.

Rothwell R. L. (1983) Erosion and sediment control at road-stream crossings. The Forestry Chronicle 59:62-66.

Shepard J. P. (2006) Water quality protection in bioenergy production: The US system of forestry best management practices. Biomass & Bioenergy 30:378-384.

Swift L. W. (1984) Gravel and grass surfacing reduces soil loss from mountain roads. Forest Science 30:657-670.

Taylor S. E., Rummer R. B., Yoo K. H., Welch R. A., Thompson J. D. (1999) What we know -- and don't know -- about water quality at stream crossings. Journal of Forestry 97:12-17.

Trimble G. R., Sartz R. S. (1957) How far from a stream should a logging road be located? Journal of Forestry 55:339-341.

Ursic S. J. (1991) Hydrologic effects of clearcutting and stripcutting loblolly pine in the coastal plain. Journal of the American Water Resources Association 27:925-937.

Ursic S. J., Douglass J. E. (1978) The effects of forestry practices on water resources. In: Proceedings of the W. Kelly Mosley environmental forum. 33-49.

Virginia Department of Forestry. (2009) Virginia's forestry best management practices for water quality.Virginia Department of Forestry, Charlotsville, VA.

Wade C. R., Bolding M. C., Aust W. M., Lakel W. A. (2012) Comparison of five erosion control techniques for bladed skid trails in Virginia. Southern Journal of Applied Forestry 36:191-197.

Wear L. R., Aust W. M., Bolding M. C., Strahm B. D., Dolloff C. A. (2013) Effectiveness of best management practices for sediment reduction at operational forest stream crossings. Forest Ecology and Management 289:551-561.

Wynn T. M., Mostaghimi S., Frazee J. W., Mcclellan P. W., Shaffer R. M., Aust W. M. (2000) Effects of forest harvesting best management practices on surface water quality in the Virginia coastal plain. Transactions of the ASAE 43:927-936.

4.0 An Approach for Estimating the Number of Forest Road Stream Crossings in Virginia

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4.1 Abstract

Forest roads and associated stream crossings are necessary for both forest management and recreational activities. Recently, industry and agency professionals have questioned stream crossing permitting processes, current guidelines, and the effectiveness of associated best management practices (BMPs). The Virginia Department of Forestry (VDOF) currently records BMP application rates. However, they do not track implementation and construction rates for individual crossing types. This project was designed to estimate haul road stream crossing construction rates in the Piedmont region of Virginia. Surveys were completed by VDOF water quality engineers during their BMP audit process. They collected data on the presence of stream crossings and the level of BMPs on the crossings over one year of timber harvest tract audits (240 sites). VDOF timber harvest notification was also used to identify an additional 400 timber harvests for which satellite imagery was viewed to provide a second estimate of the presence of stream crossings and the corresponding harvest type and species composition. The VDOF survey estimated 774 haul road stream crossings were constructed in a 12 month period with a BMP implementation rate of 66%. The satellite imagery resulted in an estimated 1,067 haul road stream crossings per year, which is relatively similar to the more expensive estimate provided by on the ground visits.

4.2 Introduction

Forest operations in the United States are considered to be non-point sources of pollution (NPSP). However, recent court proceedings (Fletcher, 2011) and literature reviews (Boston and Thompson, 2009; Boston, 2012) have questioned the adequacy and legality of not treating ditched forest roads and stream crossings as point sources of pollution. While general forest operations (harvesting, site preparation, competition control and fertilization) have few long term impacts on water quality; roads, skid trails and stream crossings can be areas of concern for stream sediment (Patric, 1976; Yoho, 1980; Kochenderfer and Helvey, 1987; Binkley and Brown, 1993). The concern for forest managers relates to uncertainty of future regulatory processes. For example, the Environmental Protection Agency has struggled with defining NPSPs and there has been a lack of consensus on what constitutes a NPSP (Hewlett and Troendle, 1975). In addition, there is a lack of adequate in-stream criteria for water quality (Corner et al., 1996). Recent court proceedings have highlighted the need for forest managers and the regulatory community work together to improve both the environmental and economic effectiveness of sediment reduction measures (Boston, 2012).

4.2.1 Best Management Practices

Forest harvesting has been shown to have minimal long term negative effects on water quality (Sullivan, 1985; Corner et al., 1996). However, road building can be correlated with increases in sediment yield (Beschta, 1978; Reid and Dunne, 1984). Early studies of forest road impacts on water quality included the relationship between road location and sediment (Trimble and Sartz, 1957) conducted one of the early studies on forest road location and stream sediment. They concluded that including a buffer strip between the road and stream would minimize sedimentation and that increased slope would require a greater buffer width. The Federal Water Pollution Control Act of 1972 resulted in many states developing Best Management Practice

(BMP) guidelines to address water quality concerns associated with forest operations, including roads and stream crossings. In general, BMPs that increase surface cover and roughness, and increase rainfall interception have been found to be effective in reducing soil erosion. These measures include vegetation establishment, application of slash or straw mulch (Grace et al., 1998; Sawyers et al., 2012; Wade et al., 2012; Wear et al., 2013), hydroseeding, and terracing (Megahan et al., 2001), grass seeding for low volume roads, and rock application on haul roads (Swift, 1984; Kochenderfer and Helvey, 1987).

Numerous studies have demonstrated the sediment reduction efficacy of BMPs related to skid trails (Sawyers et al., 2012; Wade et al., 2012), skid trail stream crossings (Wear et al., 2013), as well as reopening legacy haul roads (Brown et al., 2013). In addition, stream side management zone BMPs (Arthur et al., 1998) have been found to reduce erosion while general BMP compliance can reduce storm flow and pollutant levels (Wynn et al., 2000). Aust and Blinn (2004) surveyed literature and concluded that BMPs are effective at reducing erosion. Aust et al. (1996) estimated BMP benefit-cost ratios to vary between 0.15 and 0.55 and concluded that benefit-cost ratios may be site specific. Though BMPs have been demonstrated to be generally effective in reducing erosion and sediment delivery, the efficiency of BMPs for different site conditions is not fully understood (Edwards and Williard, 2010). Anderson and Lockaby (2011) identified the optimization of BMPs as a gap in the current literature. Further, state BMP programs have not effectively incorporated long term research investigating the effectiveness of BMPs into guidelines (Ice et al., 1997). In Virginia BMPs at and near stream crossings are of particular concern due to their proximity to stream channels and BMP implementation rates (Lake and Poirot, 2013).

4.2.2 Stream Crossings

Studies investigating the various types of forest stream crossings and different levels of BMPs are limited and it is especially difficult to separate the sediment impact of the stream crossing structure from the road approach (Thompson et al., 1995; Taylor et al., 1999). While investigating the sediment production of two bridges and a culvert installed in the Piedmont, Thompson et al. (1995) found that the bridge produced the lowest sediment mass. However, road approach BMPs were as important as stream crossing structures and associated BMPs. Aust et al. (2011) found similar results when investigating 23 Virginia Piedmont stream crossings. Portable panel bridges were found to produce the least amount of sediment, but the approach was found to be as important as the stream crossing structure. Additionally, they concluded that crossing structures which are properly selected and installed with appropriate BMPs can result in minimal water quality effects.

Stream crossings have been found to have negative impacts on water quality (Thompson et al., 1995; Taylor et al., 1999; Aust et al., 2011). The costs associated with the crossings and associated BMPs have been quantified through surveys of logging contractors (McKee et al., 2012) as well as case study crossing installations (Visser et al., 2003). Costs reported by McKee et al. (2012) ranged from $975 for the construction of a ford crossing to $1,586 for a culvert, $2,857 for wooden bridges and $11,246 for steel bridges. Fords were again found to be the least expensive crossing structure when Visser et al. (2003) investigated an improved ford, panel bridge, and low water crossing in the Ridge and Valley region of Virginia. Although stream crossing construction costs and BMP effectiveness have been well documented the total number of stream crossings constructed for forest operations in Virginia is unknown.

4.2.3 Remote Sensing

To better understand the impacts of forest road stream crossings on water quality at a larger scale, the number of stream crossings must be estimated. Records of the number of crossings installed per year in states which do not require a harvest notification and/or do not require a site visit by the regulatory agency are limited. Remote sensing and aerial photography have been used for decades as valuable planning tools. Use of Google Earth to remotely collect data on the quality of public open space was found to reduce the time required to collect the data by 90% while showing no statistical difference in the quality scores between remote data collection and field visits (Taylor et al., 2011). Google Earth is also an effective measure for coarse observations in which large areas can be investigated at a relatively low level of detail and can significantly reduce the cost of data collection, when compared to in person site visits (Clarke et al., 2010). Though Clarke et al. (2010) and Taylor et al. (2011) utilized Google Earth for assessments of resources in urban environments, it has also been used to investigate forest biomass (Ploton et al., 2011) and fish farming with stationary cages (Trujillo et al., 2012). While Google Earth is an efficient tool for collecting coarse scale data in natural environments where field visits may be limited due to cost or other access restrictions.

4.2.4 Objectives

The sediment reductions and effectiveness of BMPs have been well documented (Aust and Blinn, 2004) and the financial costs of installing BMPs have been estimated (McKee et al., 2012). However, the state-wide costs and sediment impacts of stream crossings are not well understood due to lack of data on the number of stream crossings installed per year. This research study was designed to meet the following objectives:

1) Estimate the total number of haul road stream crossings, the total length of haul roads, harvested species, and harvest method in Virginia using remote sensing (Google Earth),
2) Estimate the total number of haul road stream crossings by crossing type and level of BMPs using VDOF field audits.
3) Compare the haul road stream crossing estimates from remote sensing and VDOF field visit methods.

4.3 Methods

4.3.1 Estimating Numbers of Crossings

Stream crossings by type and BMP implementation level were estimated. Estimations of crossing installation rates were conducted using two approaches. At a coarse scale, remote sensing data was collected using Google Earth (400 harvest sites). More detailed data was collected from a smaller sample (240 harvest sites) provided by VDOF Water Quality Engineers.

Google Earth provided initial estimates of crossing installation frequency. Two years (2010 and 2011) of timber harvest locations based upon mandatory harvest notifications were provided by the VDOF which included the latitude and longitude of each harvest tract as determined by a VDOF county forester using a hand held GPS unit. VDOF surveys were conducted on sites which were harvested in 2012 and 2013. Older harvest notification data were used for Google Earth to decrease the probability of selecting sites with photos taken prior to the harvest. Four-hundred (approximately 3.5%) of the 11,226 harvest tracts were randomly selected and investigated using Google Earth to provide for an estimate of the proportion of sites with stream crossings with a confidence interval of 0.10 and α=0.10. The coordinates were entered into Google Earth and the presence of streams and haul roads were used to determine location of potential stream crossings. In addition to the presence of stream crossings, data were collected on the haul road length (measured with the built in path length measuring tool in the Google Earth software), harvest type (clear cut, partial harvest, mixed), and species composition (hardwood or pine). Figure 7 is an example of a clear cut pine harvest with one skid trail and two haul road stream crossings.

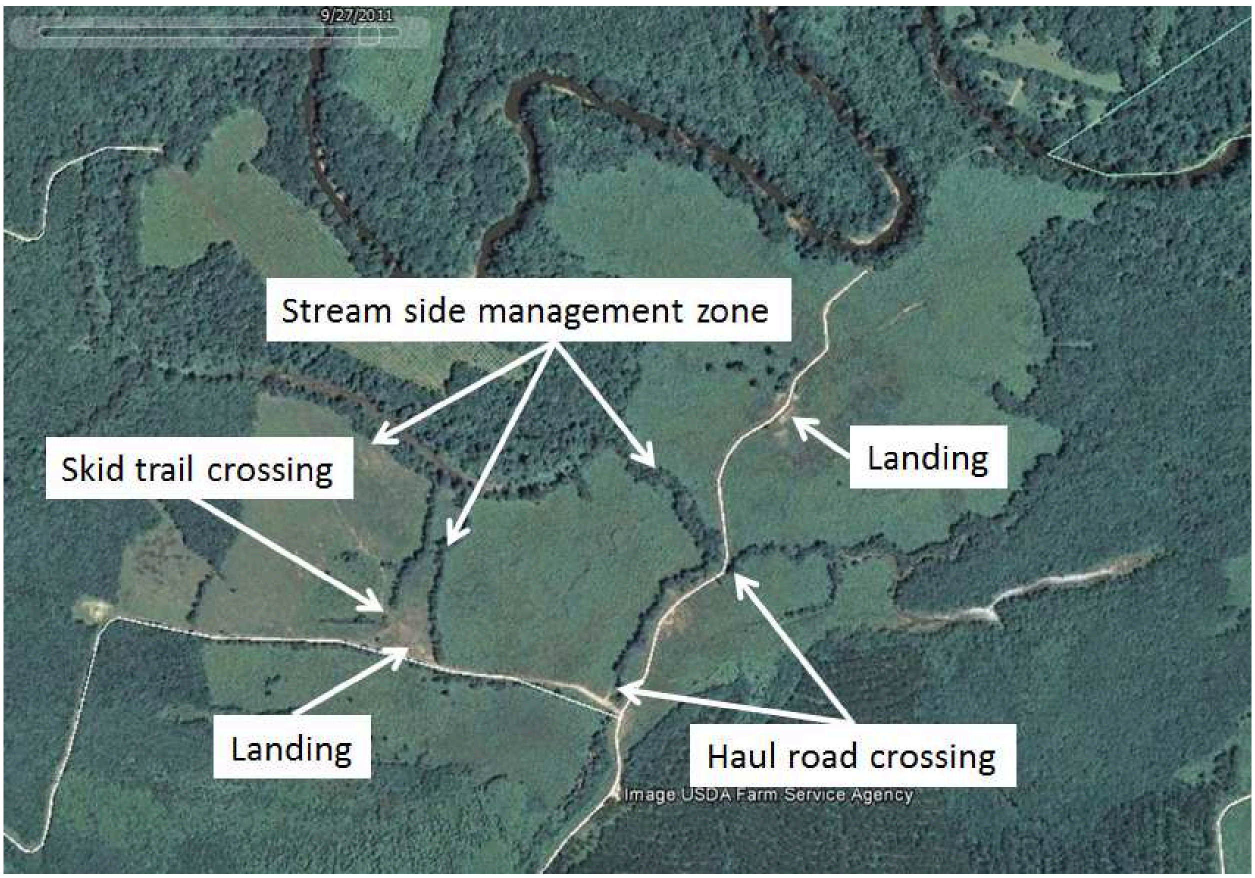

Figure 7: Google Earth image of harvest site with two haul road stream crossings and one skid trail stream crossing. Crossings, stream side management zones and log landings are marked on the pine clear cut harvest.

Estimates of crossing frequency by crossing type and level of BMP implementation were conducted utilizing data provided by the VDOF Water Quality Engineers. The Engineers audit

240 of the 5,613 harvest tracts per year. The average number of harvests in 2010 and 2011 (5,613) was used for annual estimates of Google Earth and VDOF survey data. Engineers were provided a questionnaire, in addition to their standard BMP compliance audit, to complete during their regular audit process which included questions regarding crossing use (haul road or skid trail), crossing type (i.e. ford, culvert, bridge, etc.), crossing permanency, BMP implementation level, and if a citation was issued. BMP compliance data were based upon the level of BMP implementation with BMP- being sites with BMP implementation below the state standards; BMP sites that met the state BMP recommendations; and BMP+, where BMP implementation was beyond the state recommendations. The questionnaire was completed by all engineers on all audits for one year, resulting in 240 responses.

4.4 Results

4.4.1 Haul Road Crossings in Virginia

Google Earth™ was used to investigate the presence of haul road stream crossings on past timber harvest tracts in Virginia. Of the 400 tracts considered, 80 of the sites were eliminated from analysis due to poor resolution in the satellite photo or the photo supplied in the software was not current. The remaining 320 harvest tracts were analyzed for skid trail and haul road stream crossing presence and frequency as well as haul road length, species composition (Pine or Hardwood) and harvest type (Clear Cut, Selection or Mixed). Using the Google Earth data collection method, 19% of harvest tracts (1,067 of 5,613) had haul road stream crossings. Harvests in pine stands were found to have a significantly higher probability of containing a haul road stream crossing than hardwood or mixed stands, though there was no difference in skid crossings between species compositions (Table 12). Harvest type showed no difference in probability of haul road stream crossings, however clear cut harvest were found to have a significantly higher probability of containing a skid trail stream crossing.

Table 12: Probability of a harvest tract having a haul road or skid trail stream crossing by stand composition and harvest type as observed using Google Earth, (N=320). Values followed by different letters in the same column are statistically different according to a Post-hoc Tukey HSD test (α=0.05).

Explanatory Variable		Mean (Haul Crossing) %		Mean (Skid Crossing) %	
Stand Composition	Pine	P=0.0024	32 a	P=0.3741	83 a
	Hardwood		11 b		58 a
	Mixed		0 b		65 a
Harvest Type	Clear Cut	P=0.3375	19 a	P=0.0152	87 a
	Selection		18 a		36 b
	Clear Cut/Selection		67 a		33 b

The VDOF audit survey method resulted in an estimated 774 haul road stream crossings constructed per year. Culverts with BMPs which meet the state standards contained the largest portion (257 crossings per year) (Table 13). When comparing the Google Earth estimate to the VDOF estimate there is near a 300 crossing per year difference between the two estimates (Table 15). The VDOF data showed a BMP implementation rate of 66% which is the combined proportion of BMP and BMP+ treatments for stream crossing (i.e. sites which with BMP implementation at or beyond the state recommendation).

4.4.2 Cost Impacts

Crossing installation costs (construction and BMP implementation costs) were combined with the annual crossing installation rates by crossing and BMP level to estimate the total monetary cost of crossings being installed. Table 14 represents costs with the current installation and implementation rates as estimated using the VDOF audit surveys and point estimates of crossing construction and BMP implementation costs (Chapter 2). The bridge was the most expensive crossing to build (Table 15). However, it was not the most expensive state wide due to the relatively low rate of installation of permanent bridge crossings. The culvert resulted in the greatest annual state wide cost with over $1.1 million of the estimated $2.4 million total being attributed to culvert crossings (including all BMP levels).

Table 13: State wide annual stream crossing construction rates by BMP level with associated BMP implementation rate, estimated from VDOF surveys.

BMP Level	Ford	Reinforced Ford	Culvert	Bridge	Implementation Rate
BMP-	23	0	234	0	33%
BMP	164	0	257	47	63%
BMP+	0	23	23	0	3%
Total	187	23	515	47	100%

Table 14: State wide Crossing and BMP cost for all crossings and BMPs with annual cost estimates using VDOF observed data with upper and lower 90% confidence intervals of crossing frequency.

Crossing	BMP Level	Crossings Per Year (Lower 90%)	Mean (crossings per year)	Crossings Per Year (Upper 90%)	Cost (mean)
Bridge	BMP-	1	1	43	$5,368
	BMP	1	47	68	$265,926
	BMP+	1	1	5	$5,858
Culvert	BMP-	105	234	362	$835,236
	BMP	116	258	399	$1,072,745
	BMP+	11	23	36	$107,588
Ford	BMP-	6	23	40	$4,207
	BMP	45	164	283	$68,722
	BMP+	1	23	73	$43,769
Annual Total		287	774	1,309	$2,409,420

4.4 Discussion

Applications of Google Earth for stream crossing frequency data collection were imperfect due to the lack of ability to collect site specific data that could only be collected from an onsite visit. However, the larger sample size and ease of collection allows for an efficient method for collecting preliminary data or data in instances where site visits are not practical as it has been used in other disciplines (e.g. Clarke et al., 2010; Ploton et al., 2011; Taylor et al., 2011; Trujillo et al., 2012). When comparing the total crossing installation frequency between the two methods we found that the Google Earth total crossing per year estimate is within the 90% confidence interval of the VDOF audit derived estimate. Though neither method is perfect, the agreement between the methods suggests that the estimate utilized is within reason.

BMP implementation rates (66% of stream crossings in compliance with VA BMPs) were found to be lower than the 91.5% compliance rate for stream crossings published by the VDOF (Lakel and Poirot, 2013). This difference could be due to the VDOF audit survey requiring all individual pieces of a crossing to meet the requirements, regardless of the presence or likelihood of eroded material entering a stream. An increase in sediment associated with a lack of BMP compliance reinforces the concern regarding water quality and erosion associated with stream crossings, roads and skid trails (Patric, 1976; Yoho, 1980; Kochenderfer and Helvey, 1987; Binkley and Brown, 1993; Briggs et al., 1998). Increased BMP requirements could reduce sedimentation rates, however, those implementing the BMPs must believe they are useful or the rate of compliance could decrease (Brynn and Clausen, 1991).

Gaining a greater understanding of the impact of crossing structures and associated BMPs is crucial. It is also important to understand the impact of stream crossings and any upslope areas that could contribute both surface and subsurface water as well as eroded material which could be delivered to the stream through the crossing structure. The road approach to the crossing can be a significant source of sediment (Brown et al., 2013). Proper road planning, including layout and drainage structures can minimize the sediment contribution of the road approach. Though specific BMPs have been found to be effective (e.g. Aust et al., 1996; Wynn et al., 2000; Aust and Blinn, 2004; Edwards and Williard, 2010; Worrell et al., 2011; McKee et al., 2012; Sawyers et al., 2012; Wade et al., 2012; Brown et al., 2013; Wear et al., 2013) an optimal level of BMPs has not been determined. Further research should focus on addressing the optimal level of BMPs by considering stream sediment and economic concerns on local, state and regional scales.

4.5 Conclusions and Recommendations

Current BMP implementation rates are responsible for reducing negative impacts from haul road stream crossings. Improvements in implementation rates could further protect water quality at a relatively small financial cost to landowners, managers, and logging contractors. In order for further decisions to be made regarding the proper level of erosion prevention measures, researchers and agency representatives must work together to determine the level of stream sedimentation that is acceptable based upon economic and biological impacts. Further work needs to include the economic and biological impact of stream sediment, including in-stream water quality criteria, rather than only approaching stream sediment from a cost effectiveness ratio. Use of a cost-benefit approach would require understanding the full economic benefit of decreased sedimentation on a per unit basis.

Field work, data collection and analysis required for this research has provided insight into how land managers and policy makers may be able to improve the overall effectiveness of BMP programs in terms of both cost and sediment yield and is summarized in the following recommendations.

1. Improve the crossing selection methods for land managers. This study did not address the proper application of stream crossings, however installing the proper crossing for a given scenario could be more important than proper application of erosion control measures on a crossing. BMPs should include crossing selection criteria and methods.
2. The use of aerial or satellite photographs allows for estimation of crossing construction and use. Field surveys are still required to collect data on the crossing structure and BMPs used on each individual crossing.

4.6 Literature Cited

Anderson C., Lockaby B. (2011) Research gaps related to forest management and stream sediment in the United States. Environmental Management 47:303-313.

Arthur M. A., Coltharp G. B., Brown D. L. (1998) Effects of best management practices on forest streamwater quality in eastern Kentucky. Journal of the American Water Resources Association 34:481-495.

Aust W. M., Blinn C. R. (2004) Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years. Journal of Water, Air and Soil Pollution 4:5-36.

Aust W. M., Carroll M. B., Bolding M. C., Dolloff C. A. (2011) Operational forest stream crossings effects on water quality in the Virginia piedmont. Southern Journal of Applied Forestry 35:123-130.

Aust W. M., Shaffer R. M., Burger J. A. (1996) Benefits and costs of forestry best management practices in Virginia. Southern Journal of Applied Forestry 20:23-29.

Beschta R. L. (1978) Long-term patterns of sediment production following road construction and logging in the Oregon coast range. Water Resources Research 14:1011-1016.

Binkley D., Brown T. C. (1993) Forest practices as nonpoint sources of pollution in North America. Journal of the American Water Resources Association 29:729-740.

Boston K. (2012) Impact of the Ninth Circuit Court ruling (Northwest Environmental Defense Center v. Brown) regarding forest roads and the Clean Water Act. Journal of Forestry 110:344-346.

Boston K., Thompson M. (2009) An argument for placing logging roads under the NPDES program. Ecology Law Currents 36:169-176.

Briggs R. D., Cormier J., Kimball A. (1998) Compliance with forestry best management practices in Maine. Northern Journal of Applied Forestry 15:57-68.

Brown K. R., Michael Aust W., McGuire K. J. (2013) Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia piedmont. Forest Ecology and Management 310:836-846.

Brynn D. J., Clausen J. C. (1991) Postharvest assessment of Vermont's acceptable silvicultural management practices and water quality impacts. Northern Journal of Applied Forestry 8:140-145.

Clarke P., Ailshire J., Melendez R., Bader M., Morenoff J. (2010) Using Google Earth to conduct a neighborhood audit: Reliability of a virtual audit instrument. Health & Place 16:1224-1229.

Corner R. A., Bassman J. H., Moore B. C. (1996) Monitoring timber harvest impacts on stream sedimentation: Instream vs. Upslope methods. Western Journal of Applied Forestry 11:25-32.

Edwards P. J., Williard K. W. J. (2010) Efficiencies of forestry best management practices for reducing sediment and nutrient losses in the eastern United States. Journal of Forestry 108:245-249.

Fletcher W. A. (2011) Northwest environmental defense center v. Brown, 640F.3d 1063. United States 9th Circuit Court of Appeals.

Grace J. M., Rummer B., Stokes B. J., Wilhoit J. (1998) Evaluation of erosion control techniques on forest roads. Transactions of the ASABE 4:383-391.

Hewlett J. D., Troendle C. A. (1975) Non-point and diffused water sources: A variable source area problem. In: Proceedings, Watershed Management Symposium, 11-13 August 1975, Logan, Utah: American Society of Civil Engineers, New York, NY. 21-46.

Ice G. G., Stuart G. W., Waide J. B., Irland L. C., Ellefson P. V. (1997) Twenty-five years of the Clean Water Act: How clean are forest practices? Journal of Forestry 95:9-13.

Kochenderfer J. N., Helvey J. D. (1987) Using gravel to reduce soil losses from minimum-standard forest roads. Journal of Soil and Water Conservation 42:46-50.

Lakel W. A., Poirot M. (2013) Silvicultural best management practices implementation monitoring for Virginia, 2012. Virginia Department of Forestry, Charlottseville, VA.

McKee S. E., Shenk L. A., Bolding M. C., Aust W. M. (2012) Stream crossing methods, costs, and closure best management practices for virginia loggers. Southern Journal of Applied Forestry 36:33-37.

Megahan W. F., Wilson M., Monsen S. B. (2001) Sediment production from granitic cutslopes on forest roads in Idaho, USA. Earth Surface Processes and Landforms 26:153-163.

Patric J. H. (1976) Soil erosion in the eastern forest. Journal of Forestry 74:671-677.

Ploton P., Pélissier R., Proisy C., Flavenot T., Barbier N., Rai S. N., Couteron P. (2011) Assessing aboveground tropical forest biomass using Google Earth canopy images. Ecological Applications 22:993-1003.

Reid L. M., Dunne T. (1984) Sediment production from forest road surfaces. Water Resources Research 20:1753-1761.

Sawyers B. C., Bolding M. C., Aust W. M., Lakel W. A. (2012) Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia piedmont. Journal of Soil and Water Conservation 67:300-310.

Sullivan K. (1985) Long-term patterns of water quality in a managed watershed in Oregon: Suspended sediment. Journal of the American Water Resources Association 21:977-987.

Swift L. W. (1984) Gravel and grass surfacing reduces soil loss from mountain roads. Forest Science 30:657-670.

Taylor B. T., Fernando P., Bauman A. E., Williamson A., Craig J. C., Redman S. (2011) Measuring the quality of public open space using Google Earth. American Journal of Preventive Medicine 40:105-112.

Taylor S. E., Rummer R. B., Yoo K. H., Welch R. A., Thompson J. D. (1999) What we know -- and don't know -- about water quality at stream crossings. Journal of Forestry 97:12-17.

Thompson J. D., Taylor S. E., Yoo K. H., Brinker R., Tufts R. A. (1995) Water quality impacts from different road stream crossings. Presented at the Council on Forest Engineering - Sustainability, Forest Health and Meeting the Nations Needs For Wood Products, Corvallis, OR.

Trimble G. R., Sartz R. S. (1957) How far from a stream should a logging road be located? Journal of Forestry 55:339-341.

Trujillo P., Piroddi C., Jacquet J. (2012) Fish farms at sea: The ground truth from Google Earth. PloS ONE 7:e30546.

Visser R., Aust W. M., Gallagher T., Roberts T., Poirot M. (2003) Cost of six different stream crossing options in the Appalachian area. Southern Journal of Applied Forestry 27:66-70.

Wade C. R., Bolding M. C., Aust W. M., Lakel W. A. (2012) Comparison of five erosion control techniques for bladed skid trails in Virginia. Southern Journal of Applied Forestry 36:191-197.

Wear L. R., Aust W. M., Bolding M. C., Strahm B. D., Dolloff C. A. (2013) Effectiveness of best management practices for sediment reduction at operational forest stream crossings. Forest Ecology and Management 289:551-561.

Worrell W. C., Bolding M. C., Aust W. M. (2011) Potential soil erosion following skyline yarding versus tracked skidding on bladed skid trails in the Appalachian region of Virginia. Southern Journal of Applied Forestry 35:131-135.

Wynn T. M., Mostaghimi S., Frazee J. W., Mcclellan P. W., Shaffer R. M., Aust W. M. (2000) Effects of forest harvesting best management practices on surface water quality in the Virginia coastal plain. Transactions of the ASABE 43:927-936.

Yoho N. S. (1980) Forest management and sediment production in the south - a review. Southern Journal of Applied Forestry 4:27-36.

5.0 Conclusions

5.1 BMP Effectiveness

Forest roads and stream crossings have been identified as an area of concern for forest managers in terms of water quality (e.g. Megahan, 1972; Beschta, 1978; Reid and Dunne, 1984; Croke and Mockler, 2001; Croke et al., 2005; Surfleet, 2011). The use of BMPs has been found to reduce erosion and sedimentation from forest roads (e.g. Brown et al., 2015), skid trails (e.g. Sawyers et al., 2012; Wade et al., 2012), and stream crossings (e.g. Wear et al., 2013). Further, Taylor et al. (1999) suggested a need for research on stream crossings and stream crossing BMPs with studies which separate the stream crossings structure from the stream crossing approach. This study was developed as three separate but related studies with the goal of addressing stream crossing erosion and sedimentation issues on a site specific scale and expanding to a state wide scale to gain a better understanding of financial and environmental costs of current BMPs. The first study consisted of rainfall simulation on three stream crossings with three different levels of BMPs. The second study investigated the pre and post crossing installation time phases on stream sediment. The third study used remote sensing and field data collection to estimate the number of stream crossings installed in VA in a given year.

5.2 Rainfall Simulation

While conducting rainfall simulation experiments the use of BMPs reduced stream sediment contribution. However, only the ford and culvert crossings showed a reduction in sediment with increased BMPs, the bridge crossing sediment contribution increased with additional BMPs. During this experiment sediment was entering the stream channel beneath the bridge panels, flowing through the gabion baskets. This sediment likely originated at or near the road and was traveling through a subsurface channel prior to flowing into the gabion basket.

Removal of the crossing to investigate the source was not feasible. However, the presence of this sediment source illustrated how BMPs do not always work perfectly. The increased cost and increased stream sediment from the bridge site illustrates the site specific benefit-cost ratios found by Aust et al. (1996). This subsurface flow path was unforeseen during construction activities and resulted in a large enough sediment contribution that the additional levels of BMPs did not result in a decreased sediment contribution downstream. This source of sediment may have also been responsible for the lack of significant differences in the pre and post construction stream monitoring.

BMPs on the bridge crossing did not reduce sediment loading; however, even with minimal BMPs the bridge produced a low level of sediment when compared to the culvert and ford crossings with minimal BMPs. The low level of sediment production from the bridge crossing in comparison to the culvert and ford is similar to results of other studies (e.g. Thompson et al., 1995; Aust et al., 2011). This is likely due to minimal channel disturbance and the reduction of connectivity between the road approach and the stream channel. The bridge crossing was a very effective crossing structure in terms of sediment reduction and ease of travel. Concerns with the bridge crossing include cost and longevity. The use of a steel panel bridge would increase the useable life span of the bridge, however, would greatly increase the cost of the bridge. Further, the use of a bridge in other crossing locations may not have been appropriate due to road location, channel shape/size and cost considerations.

The culvert crossing was also a relatively costly crossing to construct. The initial rainfall simulation on the culvert resulted in a large sediment contribution. However, the implementation of increased levels of BMPs resulted in a large decrease in sediment production. The cost of the increased BMPs was relatively small when compared to the base construction cost for the culvert. The ford crossing also showed a decrease in stream sediment contribution with increased BMPs. The ford crossing did have a large increase in price when implementing the BMP+ treatment due to the application of Geo-Web and gravel in the stream channel. Both the culvert and ford required channel excavation which produced approximately 13 Mg of sediment in an eight hour day. All three crossings resulted in similar sediment contributions when additional levels of BMPs (BMP+) were used. However, these levels of BMPs may not be feasible in application if the logging operators and land managers do not believe they will be effective or they believe the cost to implement them is too great (Brynn and Clausen, 1991).

During the rainfall simulation experiments on all three crossings the crossing structure was disconnected from the road approach and water was only applied to the crossing structure. The road approach to the stream crossing was not included in the rainfall simulation and could have a significant effect on stream sediment at stream crossings (Brown et al., 2013; Brown et al., 2015) if the eroded material and water transporting the material is not controlled and diverted prior to entering the stream crossing structure. The different areas of contribution (e.g. road surface, fill slope, disturbed soil, etc.) within the stream crossing structures were not differentiated. The order of application of BMPs was based upon the order of implementation expected in the field as well as operational constraints. The culvert received rainfall simulations on a bare crossing, culvert crossing with rocked road surface, and a culvert with a rocked road surface and rocked and mulched fill slopes. It is unclear how the road surface and fill slope contribute to sedimentation as individual components. Future research which can identify the contributing area through the use of sediment tracers, or other applicable methods, could better guide land managers and policy makers to determine the importance of erosion mitigation measures on the various areas of crossing structures.

5.3 Pre and Post Crossing Installation

The pre and post installation analysis showed that there was little difference in sediment levels when installing a ford with additional BMPs. However, both the bridge and culvert showed reductions in mean daily sediment contribution when the old legacy ford stream crossing was updated with a designed crossing with additional BMPs. Although the mean sediment level decreased for the bridge and culvert crossings, the amount of variability and the storm response increased following installation of the improved crossings. The increased storm response and variability is likely due to the time since disturbance. The pre installation crossings had not been disturbed in several years and possibly several decades. The post installation data collection continued for less than one year post installation. A longer post installation data collection period may have resulted in a reduction in storm response and variability in sediment contribution as the time since disturbance increased.

Traffic through the crossings was minimal during the pre and post construction time periods. Due to the minimal amount of traffic observed neither the effect of traffic on water quality nor differences between crossings with heavy traffic were observed. The ford crossing results in vehicles traveling through the stream channel which can result in sediment from channel disturbance as the tires contact the stream bed as well as mud being washed from tires in the channel. The crossings were built based upon what was determined to be the most appropriate crossing for the site. The effectiveness of each crossing structure in a different location is unknown. Due to the scale and scope of conducting such experiments they are unlikely. Construction of a given crossing type, testing and then removing the crossing and replacing it with a different crossing structure would result in significant stream channel and soil disturbance that may not be characteristic of the crossing types being considered. Further, different crossing types were tested on 3 separate, but similar, streams on one road. However, each crossing had unique road approach characteristics, including the road slope, width and the angle at which the road entered the stream channel.

5.4 Stream Crossing Cost Effectiveness and State Level Estimation

Based upon the VDOF surveys conducted it is estimated that 774 crossings are constructed each year in Virginia. Though this is an estimate, it is based upon a relatively small sample size (240 sites out of 5600 harvest tracts). The relatively low sample size resulted in only 33 observed permanent crossings. An increased sample size would allow for a more accurate prediction of crossing installation rates. Further investigation into the frequency of temporary crossings would be beneficial. In order to better understand the cost and sediment contribution of stream crossings and associated BMPs it would be beneficial to be able to compare permanent and temporary crossings in terms of both cost and sediment contribution. This comparison would require estimates of installation frequency as well as sediment contribution and costs for all types of crossings. These estimates would allow for better BMP recommendations regarding stream crossing permanency and type.

5.5 Conclusions and Recommendations

This study utilized rainfall simulation experiments at a larger scale than has been traditionally used for stream crossings. The overall scale of the rainfall simulations was similar to what others have done on roads and road approaches (e.g. Brown et al., 2015). Large scale rainfall simulations on entire crossing structures have been limited. In addition the application of crossing sediment contributions and costs to state wide crossing installation estimates has been limited. The study estimated the state wide sediment contribution and associated costs as well as how changes in BMP recommendations and/or implementation rates may alter sediment contribution and cost.

The field studies suggested that the use of stream crossing BMPs can reduce stream sediment. The resulting decreased sediment is in agreement with other recent skid trail (Sawyers et al., 2012; Wade et al., 2012), haul road (Brown et al., 2013; Brown et al., 2015) and skid trail stream crossing (Wear et al., 2013) research. Similar to Wear et al. (2013) this study utilized in stream water quality monitoring instead of upslope measures of erosion and sediment delivery. Rainfall simulation and daily water samples were used to estimate sediment loading from haul road stream crossings. Remote sensing and VDOF audit surveys were used to estimate the total number of haul road stream crossing constructed each year. All three studies provide further evidence for the effectiveness of haul road stream crossing BMPs and help to construct a larger state and region wide data set that may be used to investigate state and regional economic questions regarding haul road stream crossing BMPs.

Though this research and other recent studies have found that BMPs have the potential to decrease sediment, the impact of this reduction needs further investigation. Increased BMP recommendations are only worthwhile if they are implemented and the land managers may not implement them if they don't believe they are necessary or cost effective (Brynn and Clausen, 1991). Prior to changing BMP requirements an economic analysis should be conducted to determine the economic benefit of sediment reduction in comparison to the economic cost of that reduction on a per unit basis. In addition, the likelihood of operators to implement BMPs should be investigated. Additional recommendations or requirements may persuade operators to abandon the use of BMPs which could result in decreased BMP implementation.

Further research should include investigation of state and region wide crossing installation frequencies and trends. The field studies were designed to meet the crossing specific criteria outlined by Taylor et al. (1999) and the state wide estimations were developed to gain a greater understanding of the cost and sediment contribution of crossing on a state wide scale. Though the number of crossings installed per year during 2010 and 2011 was estimated, a larger sample size and continued data collection could yield more accurate data with the ability to analyze changes over time. This would further aid in analysis of the larger scale impact of haul road stream crossing BMPs on water quality and economics. In addition to tracking changes over time, the use of land owner information could allow for better use of outreach and extension programs by focusing on the landowner categories which represent the greatest concern in regard to stream crossings and BMPs. A larger scale economic analysis could allow for sharper conclusions regarding the optimal level of BMPs. However, this analysis will need to incorporate the financial and biological impacts of stream sediment and BMPs as well as research regarding the likelihood of loggers and landowners to apply various BMPs as well as the social aspects including public perception and regulatory constraints.

5.6 Literature Cited

Aust W. M., Carroll M. B., Bolding M. C., Dolloff C. A. (2011) Operational forest stream crossings effects on water quality in the Virginia piedmont. Southern Journal of Applied Forestry 35:123-130.

Aust W. M., Shaffer R. M., Burger J. A. (1996) Benefits and costs of forestry best management practices in Virginia. Southern Journal of Applied Forestry 20:23-29.

Beschta R. L. (1978) Long-term patterns of sediment production following road construction and logging in the Oregon coast range. Water Resources Research 14:1011-1016.

Brown K. R., Mcguire K. J., Aust W. M., Hession W. C., Dolloff C. A. (2015) The effect of increasing gravel cover on forest roads for reduced sediment delivery to stream crossings. Hydrological Processes 29:1129-1140.

Brown K. R., Michael Aust W., Mcguire K. J. (2013) Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia piedmont. Forest Ecology and Management 310:836-846.

Brynn D. J., Clausen J. C. (1991) Postharvest assessment of Vermont's acceptable silvicultural management practices and water quality impacts. Northern Journal of Applied Forestry 8:140-145.

Croke J., Mockler S. (2001) Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. Earth Surface Processes and Landforms 26:205-217.

Croke J., Mockler S., Fogarty P., Takken I. (2005) Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. Geomorphology 68:257-268.

Megahan W. F. (1972) Logging, erosion, sedimentation--are they dirty words? Journal of Forestry 70:403-407.

Reid L. M., Dunne T. (1984) Sediment production from forest road surfaces. Water Resources Research 20:1753-1761.

Sawyers B. C., Bolding M. C., Aust W. M., Lakel W. A. (2012) Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia piedmont. Journal of Soil and Water Conservation 67:300-310.

Surfleet C. G. (2011) Road runoff and sediment sampling for determining road sediment yield at the watershed scale. Canadian Journal of Forest Research 41:1970-1980.

Taylor S. E., Rummer R. B., Yoo K. H., Welch R. A., Thompson J. D. (1999) What we know -- and don't know -- about water quality at stream crossings. Journal of Forestry 97:12-17.

Thompson J. D., Taylor S. E., Yoo K. H., Brinker R., Tufts R. A. (1995) Water quality impacts from different road stream crossings. Presented at the Council on Forest Engineering - Sustainability, Forest Health and Meeting the Nations Needs For Wood Products, Corvallis, OR.

Wade C. R., Bolding M. C., Aust W. M., Lakel W. A. (2012) Comparison of five erosion control techniques for bladed skid trails in Virginia. Southern Journal of Applied Forestry 36:191-197.

Wear L. R., Aust W. M., Bolding M. C., Strahm B. D., Dolloff C. A. (2013) Effectiveness of best management practices for sediment reduction at operational forest stream crossings. Forest Ecology and Management 289:551-561.