

Effectiveness of State Developed and Implemented Forestry Best Management Practices in the
United States

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ABSTRACT

The passage of the Federal Water Pollution Control Act of 1972 required states to develop forestry BMPs to help reduce potential nonpoint source pollution from forest operations. Properly applied forestry best management practices (BMPs) have since been proven to protect water quality from forest operations. This research project reviewed BMP effectiveness studies in the U.S., assessed current state developed and implemented of forestry BMPs, and developed a simple method to estimate potential erosion from forest operations for the Piedmont physiographic region based on previous studies.

Eighty-one BMP effectiveness studies were reviewed. The review of past effectiveness studies indicates that water quality protection is increased when BMPs are implemented correctly. These effectiveness studies provide states with valuable information on how their BMP guidelines are achieving the goals defined by the Federal Water Pollution Control Act.

Every U.S. state has forestry BMP guidelines. These guidelines may be non-regulatory, quasi-regulatory, or regulatory depending on the state. Twenty states reported implementing non-regulatory BMP guidelines, 19 quasi-regulatory BMP guidelines, and 11 regulatory BMP guidelines. State forestry agencies were reported as being the lead agency responsible for BMP monitoring in 35 states. The national forestry BMP implementation rate was 91% (32 states). However, states did report deficiencies for specific BMP guideline categories.

Supplementary to the reviewed BMP effectiveness studies, forest erosion studies in the southeastern U.S. that quantified erosion rates from forest operations were also reviewed. Erosion rates obtained from the literature were reviewed by operation categories (timber

harvesting, forest roads, skid trails, log landings, stream crossings, and streamside management zones) and physiographic region (Mountains, Piedmont, Gulf Coastal Plain, and Atlantic Coastal Plain). There were numerous research gaps regarding erosion rates from forest operations for all the regions except the Piedmont region. The Piedmont region was selected for developing a method to estimate potential erosion from forest operations. This erosion estimation method is a quick and potentially useful tool for estimating potential erosion; however, it is based on limited data from the Piedmont region only. The basic method approach might be considered for the other physiographic regions, but further research is needed to fill current knowledge gaps.

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EFFECTIVENESS OF STATE DEVELOPED AND IMPLEMENTED FORESTRY BEST MANAGEMENT PRACTICES IN THE UNITED STATES

1.0 Introduction

The Federal Water Pollution Control Act (FWPCA) of 1972 and its subsequent amendments required states to address nonpoint source pollution (NPSP) that occurs from forest operations (Ice et al., 2004; Phillips and Blinn, 2004; Grace, 2005). Sediment is the most significant nonpoint source pollutant associated with forest operations (US EPA, 2005; Yoho 1980). To meet the water quality goals of the FWPCA, states developed regulatory, quasi-regulatory, or non-regulatory NPSP control programs (Ice et al. (2004). Forestry best management practice (BMP) guidelines were developed and implemented by these NPSP control programs. BMP guidelines may differ between states and regions. State forestry agencies are often the lead agency in BMP guideline development; however, many states involve multiple agencies (Edwards and Stuart, 2002; Cristan et al., 2016a). Section 319 of the 1987 reauthorization of the Federal Water Pollution Control Act required states to report NPSP water quality impacts to the U.S. Congress and to create strategies to address these issues (US EPA, 2005). Every U.S. state developed a forestry BMP program by 2000 (Archev 2004; Shepard 2006).

Pollutants occurring from agriculture have impaired the highest amount of U.S. waterways (170,750 miles) while forestry is ranked 10th with 22,020 miles of impaired waterways (U.S. EPA, 2005). Yoho (1980) reported that carefully managed clearcut harvests yield less than 0.2 tons ac⁻¹ yr⁻¹ of sediment whereas carefully cultivated fields yield 7.5 tons ac⁻¹ yr⁻¹. The author also reported more intensive land management operations such as active construction yield between 48 to 219 tons ac⁻¹ yr⁻¹ of sediment. Sediment yield occurring from

harvesting timber is small when compared to agriculture and active construction. Erosion occurring from timber harvests usually ranges between 0.1 and 4.9 tons $\text{ac}^{-1} \text{yr}^{-1}$ (Aust and Blinn, 2004). The most susceptible areas of erosion from timber harvesting are associated with forest roads, skid trails, and stream crossings. These areas can be direct avenues to waterways and when erosion enters a stream, it would be classified as sedimentation.

Forestry BMP guidelines have evolved over time due to redefinitions of water quality standards (Edwards and Stuart, 2004; Archey, 2004; and Rummer, 2004). BMP guidelines may be written or revised to account for changes in water quality standards or effectiveness of current BMPs. These guidelines typically vary by state but often include similar BMP categories (timber harvest, forest road construction and maintenance, skid trails, stream crossings, streamside management zones, log landings, wetland protection and management, site preparation, reforestation, and wildfire suppression and rehabilitation) (Shepard, 2006). Northeast and Pacific Northwest states tend to have Forest Practice Act legislation (regulatory) in which they can enforce water quality infractions while Southeastern state BMP guidelines generally consist of non-regulatory guidelines (Aust and Blinn, 2004). However, some Southeastern states have quasi-regulatory BMP guidelines in which BMPs are non-regulatory but citations can be issued for water quality violations.

Forestry BMP effectiveness studies provide states with evidence and understanding on how their states BMP guidelines meet the water quality goals of the FWPCA (Cristan et al., 2016b). States use information from BMP effectiveness studies to write or revise BMP guidelines. BMP effectiveness studies have documented that properly implemented BMPs (as recommended by state BMP guidelines) minimize the effects associated with timber harvesting on water quality (Cristan et al., 2016b).

States may also evaluate the application of BMP guidelines through implementation monitoring, compliance monitoring, or audits. These evaluation methods often differ by state or region but typically follow a systematic process (Phillips and Blinn, 2004). BMP guideline implementation results are often available for individual states that conduct studies on the application of BMPs; however, there have been few studies that evaluate the status of state developed and implemented forestry BMPs on a national level. The goals of this research project were to conduct a thorough literature review of BMP effectiveness studies in the U.S., provide an updated assessment of state forestry BMP programs, and use quantified erosion rates from past studies to develop an erosion estimation method based on level of BMP implementation.

1.1 Objectives

This dissertation is divided into five chapters. Chapter one provides a short introduction of this dissertation. Chapters two through four consist of manuscripts and have been or will be submitted for peer review publication. The fifth chapter will include overall dissertation conclusions on forestry BMP effectiveness and implementation.

Chapter two is a literature review of forestry BMP effectiveness studies in the U.S. This review consisted of peer-reviewed published literature (past 20 years) that focused on how BMP implementation affected soil erosion and water quality. Objectives of this manuscript were to review, organize, and consolidate past BMP effectiveness studies. The literature was first organized into three regions of the U.S. (Northern, Southern, and Western) and then by entity that conducted the study (state, federal, academia, private, industry, and/or non-profit). There have been few published literature reviews on forestry BMP effectiveness studies with none of the published studies focusing on the entire U.S. This manuscript was written by Richard Cristan, with contributions from Dr. W. Michael Aust, Dr. M. Chad Bolding, Dr. Scott M.

Barrett, Dr. John F. Munsell, and Dr. Erik Schilling and has been published in *Forest Ecology and Management* (Cristan et al., 2016).

The third chapter consists of survey results obtained from a survey sent to forest water quality programs of each U.S. state. The survey focused on the status of state developed and implemented forestry BMPs in the U.S. The objective of this study was to provide an updated assessment of state forestry water quality programs (previous assessment conducted in 2004). Survey questions focused on forestry BMPs and included: monitoring, implementation, effectiveness, regulation, legislation, policy, agency(s) involvement, and several other topics. Along with providing an updated assessment of each states forest water quality program, BMP implementation rates were statistically tested to determine if any differences existed between state regulation and region of the U.S. This manuscript has been submitted for peer-review with the *Journal of Forestry* and is currently in review. Richard Cristan wrote this manuscript and had contributions from Dr. W. Michael Aust, Dr. M. Chad Bolding, Dr. Scott M. Barrett, and Dr. John F. Munsell.

The fourth chapter compiled forest operation erosion rate literature from the Southeastern U.S. into a database and developed a method for estimating soil erosion from forest operations in the Piedmont physiographic region of the southeastern U.S. The database is divided into four physiographic regions (Mountains, Piedmont, Gulf Coastal Plain, and Atlantic Coastal Plain) and consists of previous studies (1999-present) that documented erosion rates for individual forest operational areas (timber harvests, skid trails, log landings, forest roads, streamside management zones (SMZs), and stream crossings). The main objective of this study was to develop a quick and useful method of estimating potential soil erosion from a forest operation. Erosion rates documented in the literature database were used to formulate this method. This manuscript was

written by Richard Cristan with contributions from Dr. W. Michael Aust, Dr. M. Chad Bolding, and Dr. Scott M. Barrett and will be submitted for peer-review to the *Journal of Soil and Water Conservation*.

The final chapter summarizes the overall findings from each of the three manuscripts. This chapter summarized and tie together the key findings from the reviewed BMP effectiveness studies and erosion studies along with the BMP survey results and erosion estimation method. Future state BMP program and research needs will also be discussed. This chapter was written by Richard Cristan.

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2.0 EFFECTIVENESS OF FORESTRY BEST MANAGEMENT PRACTICES IN THE UNITED STATES: LITERATURE REVIEW

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2.1 Abstract

In response to the Federal Water Pollution Control Act (a.k.a., Clean Water Act) of 1972, forestry best management practices (BMPs) were developed and subsequently implemented to address NPS pollution during forest management. BMP guidelines vary by state and can be non-regulatory, quasi-regulatory, or regulatory. To determine how effective the guidelines for protecting water quality are, research literature relating to BMP effectiveness was evaluated. Forestry BMP effectiveness studies are often site or region specific. Therefore, BMP research in the United States was divided into three regions: northern, southern, and western. Thirty research studies were reviewed for the southern region with the majority being conducted in the Piedmont and Coastal Plain physiographic regions. The Western region had thirty-one studies, most of which were in the Pacific Border physiographic region. The northern region had twenty studies primarily in the northeastern states. Forestry BMP effectiveness research generally focused on forest water quality from timber harvesting, site preparation, forest road construction and maintenance, stream crossings, and other categories of forest operations. The literature indicates that forestry BMPs protect water quality when constructed correctly and in adequate numbers.

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Forestry BMP effectiveness studies allow state forestry BMP programs to evaluate progress in reducing non-point source pollution and achieving water quality goals established under the Clean Water Act (CWA). Furthermore, states have used research findings to change BMPs and improve their guidelines. Although forestry BMPs have been proven to protect water quality, they are still being refined to enhance their performance.

2.2 Introduction

Following passage of the Federal Water Pollution Control Act of 1972 (Clean Water Act or CWA), states developed and implemented forestry best management practices (BMPs) to reduce nonpoint source pollution (NPSP) during forest management (Phillips and Blinn, 2004). The CWA includes requirements for both point source pollution (PSP) and NPSP and defines PSP to include identifiable pollution discharge areas that are traceable to an outlet. Conversely, NPSP is pollution where discharge areas are not readily identifiable and typically include agricultural and forestry operations because a pollutant cannot be attributed to a specific site or operation and is usually induced by natural erosive processes, such as surface runoff from rainfall or snowmelt (US EPA, 2005). The CWA (section 208) defines timber harvesting and silvicultural operations as NPSP (Grace, 2005). The U.S. Environmental Protection Agency (EPA) required states to adopt NPSP control programs for forestry activities and suggest states follow either a regulatory or non-regulatory approach to meet NPSP recommendations and goals for water quality (Ice et al., 2004). In 1987, congress amended the CWA (Water Quality Act) to include Section 319 to assist states with the development and funding of state NPSP control programs (US EPA, 2005). In essence, Section 319 allows EPA to grant state forestry agencies financial assistance for implementing management programs to reduce NPSP.

Although forestry BMPs differ by state, prescriptions are typically similar in that they include some variation of the following forestry operational categories: forest road construction and maintenance, log landings (decks), skid trails, stream side management zones (SMZs), stream crossings, wetland protection and management, timber harvesting, site preparation, and reforestation. Some states have also developed additional BMPs for wildlife protection (FDACS, 2014) or woody biomass harvesting (Fritts et al., 2014).

Northeastern and Pacific Northwest (includes California) states typically follow a Forest Practice Act (FPA) that requires use of specific BMPs during forest management. In contrast southeastern states generally use a voluntary approach whereby the logger or landowner can select from a suite of BMP recommendations and decide which prescription best meets water quality protection needs. Finally, some states have quasi-regulatory BMP programs where prescriptions may be voluntary but landowners have certain legal requirements such as notifying a state agency of intent to harvest or applying for permits to install stream crossings. Regardless of the approach, all states have regulatory authority to stop or regulate ‘bad actors’ if they fail to follow recommended BMPs and damage water resources (NCASI, 1994; NCASI, 1996). State forestry agencies most commonly lead BMP implementation and compliance reports. Forestry BMP strategies, techniques, and monitoring vary significantly by state and region. States also differ regarding how they select and monitor sites to document BMP implementation and compliance.

Appropriately implemented BMPs have positive influences on stream health, including stream temperature and nutrients (Arthur et al., 1998; Clinton, 2011; Edwards and Williard, 2010; Keim and Schoenholtz, 1999; Wilkerson et al., 2006). However, sediment is typically considered to be the most significant water pollutant associated with forest management (US EPA, 2005; Yoho,

1980). Forestry BMPs have been reported to improve water quality (80-90%) when compared prior practices (Ice, 2004; NCASI, 2012; Loehle et al., 2014). BMP development has been an ongoing process which began with defining potential water quality problems, formulating solutions, adopting practical and cost-effective BMPs, and monitoring their implementation (Ice, 2004). Forestry BMP effectiveness studies evaluate whether BMP implementation fully achieves the goal of protecting water quality. Forestry BMPs will continue to evolve over time as water quality standards are redefined and performance measures are changed (Rummer, 2004). Federal and state agencies and universities have completed or have ongoing implementation and effectiveness studies (NCASI, 2012).

Literature reviews addressing the effectiveness of forestry BMPs have been previously conducted. Aust and Blinn (2004) reviewed timber harvesting and site preparation BMP research results in the eastern US. Ice et al. (2004) assessed the implementation and effectiveness of BMPs in the western US. Shepard (2006) reviewed BMP use in the US with emphasis on suitability for biomass harvesting operations. Croke and Hairsine (2006) reviewed sediment delivery in managed forests. Anderson and Lockaby (2011) evaluated the effectiveness of BMPs for sediment control in the southeastern US. These previous literature reviews focus on broader categories of operations such as timber harvesting, site preparation, and biomass harvesting while this review focuses on more specific operational categories (timber harvesting, skid trails, forest roads, streamside management zones, site preparation, etc.) and seeks to comprehensively evaluate BMP effectiveness studies for the three major wood producing regions of the US so that forest managers and agency personnel have current documentation of BMP efficacy within their operational area.

2.3 Forestry BMP Effectiveness Study Literature Review Methodology

This review provides an overview of forestry BMP effectiveness and related studies by region of the United States (US). Southern, Western, and Northern regions are based on the geographic grouping of States as noted by the Southern Group of State Foresters (SGSF), Council of Western State Foresters (CWSF), and the Northeastern Area Association of State Foresters (NAASF). This review concentrated on BMP research that was published in peer-reviewed literature, had a direct emphasis on how BMP implementation levels would affect soil erosion and or stream sedimentation, and primarily focused on relatively recent literature (past 20 years) so that the findings are more indicative of current forest operations, techniques, and equipment and BMP prescriptions. To fill in gaps, a few studies dating farther back were included in the review. However, we acknowledge that this limitation does not account for much of the early BMP research established by US Forest Service researchers at sites such as Hubbard Brook, Coweeta, Parsons, and the HJ Andrews watersheds. Our BMP efficacy definition is intentionally more inclusive than Edwards and Williard (2010) who focused only on studies that compared in-stream sediment levels to differing levels of BMP prescriptions. Finally, we include comparisons of soil erosion with different levels of BMPs as we believe it is a reasonable assumption that reduced levels of soil erosion result in reduced sedimentation.

2.4 Southern States

Thirty BMP effectiveness studies from 1985 to 2015 were reviewed and documented by state and physiographic region for the Southern US (Figure 1). The majority of effectiveness studies were conducted in the Coastal Plain and Piedmont regions since these physiographic regions have extensive areas of intensively managed forests and highly mechanized forest operations (Allen et al., 2005; Fox, 2000). The BMP effectiveness studies reviewed in the South

varied by organization conducting the study (academia, state agency(s), federal agency(s), and industry), location, included assessment of evaluations and treatments, and offered key major conclusions (Table 1).

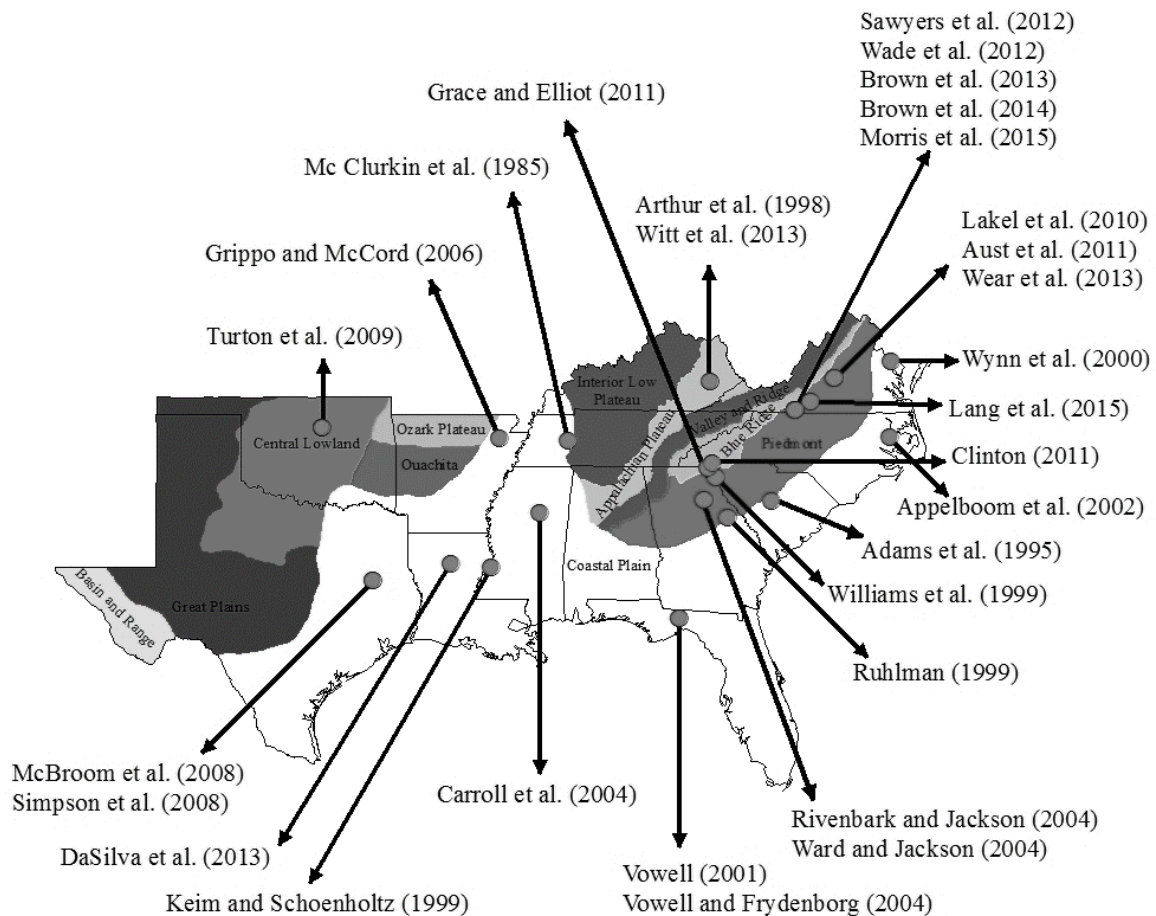


Figure 1. Reviewed BMP effectiveness studies by state and physiographic region for the southeastern United States. Locations were determined from the studies as well as Schilling and Ice (2012).

2.4.1 Academia

Twenty-two of the thirty reviewed studies were conducted by academia. The studies were divided into five categories depending on study topic (water quality, SMZ, forest roads, skid trails, and stream crossings).

2.4.1.1 Water Quality

Arthur et al. (1998) studied the effects of BMPs on stream water quality in Appalachian Plateau region of eastern Kentucky. Their study included two treatment watersheds (with BMPs and no BMPs) and one reference watershed. The authors found that water yield, suspended sediment flux, and concentrations of nitrate and other nutrients were higher on the no BMP watershed and concluded that the BMP applied watershed which included a stream buffer strip reduced water yield and sediment flux impacts.

Williams et al. (1999) evaluated the effectiveness of South Carolina BMPs on water quality in the Piedmont physiographic region. Their study consisted of monitoring four experimental watersheds on the Clemson Experimental Forest (3 treatment watersheds). Each treatment watershed was harvested and site prepared (shear, rake and pile, herbicide and burn, and natural regenerated) using South Carolina BMPs. The authors measured suspended sediment, nitrate, phosphate, pH, and water temperature and found that suspended sediments levels were 10 times lower when BMPs were applied.

Wynn et al. (2000) evaluated the impacts on surface water quality from clearcutting and site preparation in the Coastal Plain physiographic region of Virginia. Their study consisted of three watersheds (clearcut without BMPs, clearcut with BMPs, and control). The no BMP watershed resulted in significant increases in storm event concentrations and loadings (sediment, nitrogen, and phosphorus) following clearcutting and site preparation. The authors concluded that applying BMPs during harvesting and site preparation can reduce the impacts of sediment and nutrients on water quality.

Grippio and McCord (2006) conducted a bioassessment of Arkansas BMPs. The purpose of their study was to evaluate the effectiveness of Arkansas's BMPs. They evaluated benthic

macroinvertebrates and physiochemical stream parameters (water temperature, dissolved oxygen, conductivity, pH, turbidity, nitrate and ortho-phosphate, and total suspended solids (TSS)) on sites that were harvested and site prepared (ripped). The authors found that water quality improved using Arkansas BMPs.

McBroom et al. (2008) studied the effects of intensive forest operations with BMPs on stream water quality and runoff in the Coastal Plain region of Texas. Their study included two treatments: conventional operation (clearcut with herbicide site preparation) and intensive operation (clearcut with herbicide, subsoiling, and fertilization) and were compared to a previous study on the same site without BMPs (Blackburn et al. 1986). The authors found reduced water quality impacts when BMPs were applied for intensive forest operations.

DaSilva et al. (2013) assessed timber harvesting with BMPs on ecosystem metabolism in the Coastal Plain physiographic region of Louisiana. Their study focused on calculating stream metabolic rates to evaluate Louisiana BMPs. None of their calculated stream metabolic rates were significant and the authors concluded that BMPs did not have a significant effect on stream biology.

2.4.1.2 Streamside Management Zone (SMZ)

Keim and Schoenholtz (1999) assessed the effectiveness of SMZs with intensive timber harvesting in loessial bluff forests in the Coastal Plain of Mississippi. Their study had four treatments: (1) unrestricted harvest with no buffer, (2) unrestricted outside of SMZ, cable only in SMZ, (3) unrestricted harvest outside SMZ, no harvest in SMZ, and (4) reference. The authors monitored water quality (TSS, turbidity, temperature, pH, conductivity, and dissolved oxygen) for 15 months post-harvest. Keim and Schoenholtz (1999) found that timber harvests without SMZs resulted in three times the sediment concentration than the non-harvested watersheds.

They suggested eliminating equipment traffic near the stream (at least 10 m). Carroll et al. (2004) conducted a similar study to Keim and Schoenholtz (1999) within the sand-clay hills in the Coastal Plain region of Mississippi. Their study had three treatments: (1) reference, (2) clearcut with a SMZ, and (3) clearcut without a SMZ. The authors concluded that SMZs were effective in protecting water quality, as their data showed similar responses between the SMZ treatment streams and the reference streams for water quality, stream habitat indicators, and aquatic macroinvertebrate communities.

Rivenbark and Jackson (2004) evaluated the frequency of SMZ breakthroughs for the Piedmont physiographic region of Georgia to determine BMP efficiency. This study examined 30 clearcut and site prepared sites for breakthroughs and successes. The authors defined breakthroughs as where sediment entered the SMZ and entered the stream while successes were when the SMZ stopped the sediment from entering the stream. They found 187 breakthroughs on 2,773 acres which was then calculated to a breakthrough every 20 acres. The authors reported that 50% of breakthroughs were due to gullies and swales and that roads or skid trails caused 25% of breakthroughs. A similar study was conducted by Lang et al. (2015) but for the Virginia Piedmont. The authors used similar terminology and definitions but used the term partial breakthroughs instead of successes and complete breakthroughs for breakthroughs. They found 33 complete breakthroughs and 8 partial breakthroughs on 10 km of SMZs (16 sites), which averaged one complete breakthrough every 0.3 km of SMZ length. Lang et al. (2015) found that 42% of breakthroughs were due to stream crossings, 27% from gullies, and 24% from soil disturbances from timber harvesting within the SMZ.

Ward and Jackson (2004) evaluated SMZ sediment trapping efficiency for sites that were clearcut, site prepared (mechanical and chemical), and replanted in the Georgia Piedmont. Their

study had two treatments: (1) SMZ and (2) no SMZ. The authors placed a silt fence at the edge of the SMZ to accomplish the no SMZ treatment. SMZs trapped sediment from overland flow 81% of the time. Ward and Jackson (2004) also estimated that the sediment delivery ratio was 25% for their sites by taking their measured sediment from treatment two and compared it to Revised Universal Soil Loss Equation (RUSLE) predictions. Lakel et al. (2010) conducted a similar study evaluating SMZs sediment trapping ability for harvested and site prepared sites in the Virginia Piedmont. The authors compared sediment trapping of different SMZ widths and thinning levels (30.4 m, 15.2 m, 7.6 m, and 15.2 m thinned) and found that SMZs efficiency for trapping sediment ranged from 84% to 97%. Lakel et al. (2010) found the sediment delivery ratios between 3% and 14%.

Witt et al. (2013) evaluated the effectiveness of different SMZ treatments for ephemeral streams in the Cumberland Plateau of Kentucky. The treatments applied in this study were: (1) harvest, unimproved stream crossing, and no SMZ, (2) harvest, retention of only channel bank trees, and improved stream crossing, (3) harvest with 7.6 m SMZ and an improved stream crossing, and (4) control (no harvest). The authors collected water samples (TSS, turbidity, settleable solids, and sediment transport rate) and found that treatment two and treatment three resulted in significantly lower TSS and turbidity levels than treatment one (no SMZ). Treatment three was not significantly different than the control for TSS while treatment two was significantly different than the control (4) for both TSS and turbidity.

2.4.1.3 Forest Roads

Forest roads tend to be one of the major sources of sediment from forest operations. Appelbloom et al. (2002) assessed forest road practices for reducing sediment loss from forest roads in the Coastal Plain of North Carolina. The authors evaluated the effectiveness of seven

road practices and collected runoff samples. The road practices consisted of one continuous berm treatment and six non-continuous berm treatments (berm with drainage breaks). Appelbloom et al. (2002) noted that the continuous berm treatment reduced sediment loss by 99% when compared to the road not having a continuous berm. The authors also found that graveling a road can reduce sediment loss by 61% when a continuous berm is used and a grass strip (90 cm) can reduce sediment loss by 56% when compared to a road without a grass strip.

Turton et al. (2009) evaluated the effectiveness of BMPs for reducing sediment from unpaved roads in the Stillwater Creek Watershed in Oklahoma. The authors evaluated sediment yield and runoff on four rural unpaved road segments. They had two treatments and a control; treatments included: (1) widened and reshaped ditches, reshaped cut slopes, crowning of road surface, and vegetating disturbed areas and (2) crowning the road surface, geo-synthetic fabric, and 127 mm gravel. Turton et al. (2009) found that BMPs significantly reduced sediment yields.

Brown et al. (2013) assessed sediment delivery from bare and graveled stream approaches in the Virginia Piedmont. They trapped sediment from five re-graded legacy forest road stream approaches and compared them to four graveled forest road stream approaches. The authors found bare ground stream approaches produced sediment delivery rates 7.5 times greater (34 to $287 \text{ Mg ha}^{-1} \text{ y}^{-1}$) than graveled road approaches (10 to $16 \text{ Mg ha}^{-1} \text{ y}^{-1}$). Brown et al. (2013) noted that lack of both road surface cover and sufficient water control structures resulted in higher rates.

Brown et al. (2014) studied the effects of increasing gravel cover on forest roads to reduce sediment delivery to stream crossings on reopened legacy forest road stream crossings in the Virginia Piedmont. Their study had three stream approach treatments: (1) no gravel, (2) low gravel, and (3) high gravel. The authors reported higher median surface runoff TSS

concentrations for no gravel treatments (2.84 g l^{-1}), followed by low gravel treatments (1.10 g l^{-1}), and high gravel (0.82 g l^{-1}). They noted that reopened and unsurfaced stream crossing approaches can produce significant runoff and deliver sediment to streams; however, applying BMPs to the approaches significantly reduced sediment.

2.4.1.4 Skid Trails

Sawyers et al. (2012) assessed erosion control effectiveness of five overland skid trail closure methods in the Piedmont physiographic region of Virginia. Their closure treatments included: (1) waterbar only, (2) waterbar with seed, (3) waterbar with seed and mulch, (4) waterbar with hardwood slash, and (5) waterbar with pine slash. The authors measured trapped sediments and predicted erosion using the Universal Soil Loss Equation (USLE-Forest) and the Water Erosion Prediction Project (WEPP-Roads). Waterbar with seed and mulch treatments had the lowest erosion rate ($3.3 \text{ Mg ha}^{-1} \text{ y}^{-1}$) followed by waterbar with hardwood slash ($5.1 \text{ Mg ha}^{-1} \text{ y}^{-1}$), waterbar with pine slash ($5.4 \text{ Mg ha}^{-1} \text{ y}^{-1}$), waterbar with seed ($13.6 \text{ Mg ha}^{-1} \text{ y}^{-1}$), and waterbar only ($24.2 \text{ Mg ha}^{-1} \text{ y}^{-1}$). WEPP predicted similar erosion estimates to the measured data. Wade et al. (2012) conducted a similar study to Sawyers et al. (2012) in assessing erosion control effectiveness of five bladed skid trail closure techniques in the Virginia Piedmont. Their treatments were the same as Sawyers et al. (2012) and also measured trapped sediment and modeled erosion. Wade et al. (2012) also found that the waterbar with seed and mulch treatment had the best erosion control ($3.0 \text{ Mg ha}^{-1} \text{ y}^{-1}$) followed by waterbar with pine slash ($5.9 \text{ Mg ha}^{-1} \text{ y}^{-1}$), waterbar with hardwood slash ($8.9 \text{ Mg ha}^{-1} \text{ y}^{-1}$), waterbar with seed ($31.5 \text{ Mg ha}^{-1} \text{ y}^{-1}$), and waterbar only ($137.7 \text{ Mg ha}^{-1} \text{ y}^{-1}$).

Wear et al. (2013) studied the effectiveness of BMPs in reducing sediment on operational temporary skid trail stream crossings in the Virginia Piedmont. The authors applied three BMP

closure treatments on stream crossing approaches after steel bridges were removed: (1) slash, (2) mulch and seed, and (3) mulch, seed, and silt fence. They sampled water quality upstream and downstream for TSS and found slash (1) and mulch with seed treatments (2) reduced TSS, while mulch, seed, and silt fence (3) increased TSS. The authors attributed increases in TSS from treatment three to soil disturbance near the stream from silt fence installation.

2.4.1.5 Stream Crossings

Aust et al. (2011) evaluated the effects of four operational forest stream crossings (portable steel skidder bridge, culverts with poles as fill material, culverts with earth as fill material, and reinforced ford) in the Piedmont physiographic region of Virginia. The authors examined 23 operational stream crossings and approaches during four phases (initial, install, harvest, and closure) and measured total dissolved solids, pH, conductivity, temperature, and sediment concentration. They found culvert crossing approaches resulted in the highest erosion rates and that bridge crossing had the least effects on water quality. Additionally, the install and harvest phases had the greatest effect on water quality and concluded that BMPs should be followed during all phases.

Morris et al. (2015) assessed the effectiveness of BMPs for stream crossings (permanent bridge, culvert, and improved ford) in reducing sediment for the Virginia Piedmont. Their study implemented a rainfall simulation to evaluate different rainfall intensities (low: 0.5 to 1.0 inches per hour, medium: 1.5 to 2.0 inches per hour, and high: 2.0 to 2.5 inches per hour). The rainfall simulations were conducted on three BMP treatment levels: (1) minimal BMP erosion control, (2) BMP erosion control from the Virginia BMP Manual, and (3) erosion control exceeding what Virginia recommends. The culvert crossing produced 2.9 g/L of sediment concentration, while

the ford produced 1.4 g/L and the bridge produced 0.2 g/L. They concluded that Virginia BMP guidelines were effective.

2.4.2 State

Forestry BMP monitoring effectiveness was the main focus of the studies reviewed in the southern US. Adams et al. (1995) assessed the effectiveness of South Carolina BMPs by evaluating if biomonitoring can be used as a measure of determining BMP effectiveness. The authors conducted a BMP compliance check, stream habitat assessment, and a benthic macroinvertebrate bioassessment on 27 harvested sites. Adams et al. (1995) found that assessments of stream habitat and benthic macroinvertebrates were an effective approach in determining BMP effectiveness.

Vowell (2001) conducted a similar study that determined if stream bioassessments could be used to monitor BMP effectiveness on intensively managed forests in Florida. He determined a stream condition index (SCI) at each site before silvicultural treatments then conducted stream bioassessments after the treatments were applied. The author found no significant differences in the SCI and concluded that Florida recommended BMPs were effective in protecting water quality in intensively managed forests. Vowell and Frydenborg (2004) built on the study conducted by Vowell (2001), the authors evaluated intensively managed sites that included chemical applications. No significant differences in SCI were found, indicating that BMPs were effective in protecting water quality in intensively managed forests with chemical applications.

Simpson et al. (2008) evaluated the effectiveness of Texas BMPs on intensively managed silvicultural operations. The authors conducted water quality monitoring (biological and physiochemical) on four perennial streams over a four year period. They concluded that the proper application of Texas BMPs resulted in effectively protecting water quality.

2.4.3 Federal

Three studies conducted by the US Forest Service were reviewed for the southern region. Mc Clurkin et al. (1985) evaluated water quality from clearcutting loblolly pine plantations on erosive soils in the upper Gulf Coastal Plain of Tennessee. The authors evaluated stormflow exports of sediment and nutrients on eight catchments and concluded that clearcutting did not cause a significant impact on water quality as long as proper practices were applied.

Clinton (2011) evaluated riparian buffer width effectiveness by evaluating stream water quality in the Blue Ridge physiographic region of western North Carolina. The author examined cable yarding harvesting on three riparian buffer treatments (0 m, 10 m, and 30 m). Water quality measurements (chemistry, temperature, and TSS) were sampled on three of four catchments. The 0 m buffer site had increased stream nitrate concentrations and summer water temperatures, and TSS levels remained unchanged. Ten and 30 m buffer treatments reduced TSS levels. Clinton (2011) concluded that the 10 m buffer was efficient in protecting water quality.

Grace and Elliot (2011) assessed the effectiveness of forest road BMPs by evaluating storm runoff and sediment loading. Their study was conducted over a six year period in northeast Georgia (Chattahoochee-Oconee National Forest) and included three sediment control treatments (hay bale barrier, sediment basin, and sediment basin with riser control). The authors found that the sediment basin with riser control had the highest mean sediment trapping efficiency (99%), followed by hay bale barrier (97%), and sediment basin (94%). However, no significant differences were found between treatments. The authors concluded that sediment transport was reduced for all three treatments.

2.4.4 Industry

Although the forest industry funds BMP research, we located one industry study in the southern region conducted by International Paper (Ruhlman 1999). Ruhlman (1999) evaluated the effectiveness of forestry BMPs on intensively managed watersheds near the upper Coastal Plain and Piedmont physiographic border in Georgia. The author assessed water quality (chemical sampling of sediment and nutrients and benthic macroinvertebrates) on a treatment watershed of 780 acres and a reference watershed of 351 acres. The treatment watershed had an 80 foot SMZ that was selective cut. Ruhlman (1999) did not find significant differences in chemical sampling and benthic macroinvertebrate samples and concluded properly applied forest BMPs protected water quality.

Table 1. Summary of forestry BMP effectiveness studies for the southern United States by investigator(s), location, evaluations and treatments, and major conclusions.

Investigators	Region/ Location	Study conducted by	Evaluations/treatments	Major conclusions
Mc Clurkin et al. (1985)	Upper Gulf Coastal Plain (Tennessee)	Federal	Clearcutting pine plantations on fragile soils of abandoned agricultural land	Clearcutting pine plantations on fragile soils can be accomplished without significant impact on water quality if the proper forest practices are applied
Adams et al. (1995)	South Carolina	State	Compared state BMP compliance results with stream bio-assessments of benthic macroinvertebrates and stream habitats	Assessment of stream macroinvertebrates and stream habitat were an effective approach of determining BMP effectiveness
Arthur et al. (1998)	Kentucky	Academia	Effects of BMP implementation on stream water quality; evaluated suspended sediment flux, water yield, and concentrations of nutrients	Forestry BMPs were effective; buffer strips were effective in reducing water yield and sediment flux on clearcuts
Keim and Schoenholtz (1999)	Mississippi Bluff Hills Gulf Coastal Plain	Academia	Effectiveness of SMZs on loessial bluff forests; evaluated stream total suspended solids (TSS), turbidity, temperature, pH, conductivity, and dissolved oxygen	SMZs were effective in reducing overland flow and TSS concentrations due to the forest floor near the stream and stream channels not being disturbed
Ruhlman (1999)	Upper Coastal Plain (Georgia)	Industry	Effectiveness of forestry BMPs on intensively managed watersheds	Forestry BMPs were effective in protecting water quality

Williams et al. (1999)	Piedmont (South Carolina)	Academia	Effectiveness of South Carolina BMPs for harvesting and site preparation	Suspended sediments were lower on sites that applied BMPs
Wynn et al. (2000)	Coastal Plain (Virginia)	Academia	Effects of timber harvesting and site preparation BMPs on surface water quality	BMPs for timber harvesting and site preparation in the Coastal Plain region significantly reduced sediment when compared to not applying BMPs
Vowell (2001)	Coastal Plain (Florida)	State	Evaluated if stream bio-assessment could be used to monitor forestry BMPs for intensive silviculture activities	Stream condition index (SCI) was not significantly different between the reference data and treatment data; correctly implemented BMPs applied to areas around streams provide protection to stream ecosystems
Appelboom et al. (2002)	Coastal Plain (North Carolina)	Academia	Forest road practices for sediment reduction	Found that a continuous berm along the edge of a forest road reduced sediment by an average of 99%, gravel reduced sediment by an average of 61%, and a grass strip reduced sediment by an average of 56%; sedimentation from Coastal Plain roads can be reduced with appropriate forest road BMPs
Carroll et al. (2004)	Central Mississippi Upper Gulf Coastal Plain	Academia	Effectiveness of SMZs on clearcut harvests; assessed water quality, mineral soil exposure, net deposition and erosion that entered the SMZs, stream habitat indicators, and aquatic macroinvertebrates	Found a significant increase in stream temperature and macroinvertebrate density and a decrease in habitat stability when SMZs were absent; concluded that SMZs can be effective in protecting water quality

Rivenbark and Jackson (2004)	Piedmont (Georgia)	Academia	Efficiency of BMPs with preventing overland flow and sediments from reaching waterways; assessed SMZ breakthroughs (failures) on sites that were clearcut and site prepared	Roughly 50% of all breakthroughs were due to gullies and swales; runoff from forest roads and skid trails caused 25% of all breakthroughs; SMZ widths should be based on site features
Vowell and Frydenborg (2004)	Coastal Plain (Florida)	State	Supplemented Vowell (2001) study assessing stream bio-assessments for evaluating the effectiveness of forestry BMPs with the addition of chemical applications	Their conclusions were similar to the previous study in that BMPs applied to areas around streams provide protection to stream ecosystems during intensive silviculture activities including chemical applications
Ward and Jackson (2004)	Piedmont (Georgia)	Academia	Effectiveness of SMZs for reducing sediment transport from concentration overland flow on two clearcuts that applied mechanical and chemical site preparation and planting	Estimated the sediment delivery ratio was 25%; SMZs were effective for trapping sediment from concentrated overland flow with an average of 81% efficiency
Grippio and McCord (2006)	Arkansas	Academia	Effectiveness of Arkansas BMPs adjacent to timber harvests; bio-assessment of benthic macroinvertebrates and water quality	Water chemistry and benthic macroinvertebrates were not affected by timber harvesting where BMPs were applied
McBroom et al. (2008)	Western Gulf Coastal Plain (East Texas)	Academia	Storm runoff and sediment loss associated with clearcutting and stand establishment (intensive and conventional site preparation) with BMPs	First year sediment loss was significantly lower than if BMPs were not applied

Simpson et al. (2008)	Texas	State	Effectiveness of Texas forestry BMPs (2003-2007) on four perennial streams that had intensive forestry practices; monitored biological and physiochemical stream conditions	No significant differences in pre-treatment and post-treatment conditions; concluded that properly applied BMPs are effective in protecting water quality
Turton et al. (2009)	Stillwater Creek Watershed (Oklahoma)	Academia	Effectiveness of BMPs in reducing sediment from unpaved roads; evaluated runoff and sediment yield; treatments included: (1) control, (2) widened ditches, reshaped ditches, cut slopes, crowning of road surface, and vegetating disturbed areas, and (3) crowning of road surface, geo-synthetic fabric on road bed, and 127 mm gravel	Sediment yields were significantly reduced after application of both BMP treatments; Treatment 2 had a 20% reduction in sediment yield and treatment 3 had an 80% reduction in sediment yield when compared to no BMPs applied (control treatment)
Lakel et al. (2010)	Piedmont (Virginia)	Academia	Effects of SMZ widths and thinning levels on sediment moving through SMZs; SMZ treatments included widths of: 30.4 m, 15.2 m, and 7.6 m without thinning and 15.2 m with thinning; calculated sediment delivery ratio; second study (sub-watersheds) evaluated sediment at site preparation areas, fire lines, and streams; BMPs were followed on the study sites	Did not find any significant differences in sediment delivery for all SMZ treatments; second study found significant difference in sediment from the harvest, fire line, and SMZ treatment; fire lines produced 12 times more sediment as the harvest with a sediment delivery ratio of 14%; overall SMZs trapped between 84% to 97% of the erosion

Aust et al. (2011)	Piedmont (Virginia)	Academia	Effects of operational forest stream crossings had on water quality; treatments included: (1) portable steel skidder bridge, (2) culvert with poles as fill material, (3) reinforced ford, and (4) culvert with earth as fill material; assessed total dissolved solids, pH, conductivity, temperature, and sediment concentrations prior to installations, after installation, during harvest, and after road closure	The authors found that the bridge stream crossings had the least effects on water quality and the culvert had the highest estimated erosion potentials; concluded that appropriate BMPs should be followed during all periods of a timber harvest rather than waiting until closing the site to implement BMPs
Clinton (2011)	Blue Ridge (Western North Carolina)	Federal	Riparian buffer effectiveness following timber harvesting using cable yarding; three treatment buffers: 0 m, 10 m, and 30 m; sampled water chemistry, water temperature, and TSS	Concluded that riparian buffers 10 m and wider minimized impacts on stream water quality and provide an effective method to protect water quality
Grace and Elliot (2011)	Northeast Georgia	Federal	Effectiveness of forest road BMPs in controlling sediment movement; treatments included: (1) hay bale barrier, (2) sediment basin, and (3) sediment basin with riser control	Mean sediment trapping efficiency was 99% for the sediment basin with a riser control, 97% for the hay bale barrier, and 94% for the sediment basin; No significant differences in sediment trapping efficiency; sediment control structures reduced runoff by greater than 98% and sediment delivery between 94 and 97%

Sawyers et al. (2012)	Piedmont (Virginia)	Academia	Effectiveness and implementation costs of overland skid trail closure techniques within an 11.7 ha clearcut; treatments included: (1) waterbar only, (2) waterbar with seed, (3) waterbar with seed and mulch, (4) waterbar with hardwood slash, and (5) waterbar with pine slash; assessed sediment loss	Found that the mulch treatment ($3.3 \text{ Mg ha}^{-1} \text{ y}^{-1}$) was the most effective method in reducing erosion followed by hardwood slash ($5.1 \text{ Mg ha}^{-1} \text{ y}^{-1}$), pine slash ($5.4 \text{ Mg ha}^{-1} \text{ y}^{-1}$), seed ($13.6 \text{ Mg ha}^{-1} \text{ y}^{-1}$), and control ($24.2 \text{ Mg ha}^{-1} \text{ y}^{-1}$)
Wade et al. (2012)	Piedmont (Virginia)	Academia	Compared five erosion control techniques on bladed skid trails; treatments included: (1) waterbar only, (2) waterbar with seed, (3) waterbar with seed and mulch, (4) waterbar with hardwood slash, and (5) waterbar with pine slash	Similar results to Sawyers et al. (2012) in that the waterbars with mulch treatment was the least erosive followed by the slash treatment; concluded that applying mulch and slash provide good erosion control
Witt et al. (2013)	Cumberland Plateau (Kentucky)	Academia	SMZ effectiveness on ephemeral streams; four treatments: (1) no SMZ, (2) SMZ with no limitations, (3) SMZ with limitations, and (4) control; unimproved and improved stream crossings were used; sampled TSS, turbidity, and sediment transport rate	Both SMZ treatments significantly lowered TSS and turbidity when compared to the no SMZ treatment; When compared to control, treatment 2 resulted in higher TSS and turbidity while treatment 3 resulted in no difference in TSS; concluded that improved stream crossings significantly lower stream TSS and turbidity
Wear et al. (2013)	Piedmont (Virginia)	Academia	Effectiveness of BMPs for reducing sediment at operational steel bridge stream crossings; skid trail stream approaches included three treatments: (1) slash, (2) mulch and grass seed, and (3) mulch, grass seed, and silt fence; sampled TSS	Both slash and mulch with grass seed treatments effectively reduced TSS and the silt fence treatment increased TSS due to soil disturbance from installation

Brown et al. (2013)	Piedmont (Virginia)	Academia	Sediment delivery from bare and graveled stream approaches; compared road derived trapped sediment on five re-graded bare legacy stream approaches to four graveled approaches	Sediment delivery for the bare approaches were 7.5 times higher (34 to 287 Mg ha ⁻¹ y ⁻¹) than the gravel road approaches (10 to 16 Mg ha ⁻¹ y ⁻¹); concluded that sediment delivery rates were due to inadequate road surface cover and water control structures and that proper BMPs such as gravel and appropriate spacing of water control structures can reduce sediment
DaSilva et al. (2013)	Gulf Coast Plain (northcentral Louisiana)	Academia	Stream metabolic rates to test the effects of timber harvesting with Louisiana BMPs; sampled dissolved oxygen, water temperature, and stream depth above and below a timber harvest of loblolly pine	Calculated metabolic rates and none of the results were significantly changed from the timber harvest; concluded that similar timber harvests applied with Louisiana BMPs should not significantly change stream biological conditions
Brown et al. (2014)	Piedmont (Virginia)	Academia	Effect of increasing gravel cover on forest roads to reduce sediment delivery to stream crossings; reopening of legacy forest road stream crossings; treatments included: (1) no gravel, (2) low gravel, and (3) high gravel	Reopened and unsurfaced stream crossing approaches may produce significant sediment delivery and surface runoff into streams and that low cost BMPs can be used to protect water quality when reopening forest roads
Lang et al. (2015)	Piedmont (Virginia)	Academia	Identified and characterized SMZ breakthroughs (partial and complete) by frequency and potential causes for 10 km of SMZs	Found 33 complete breakthroughs and 8 partial breakthroughs over 16 sites, averaging 1 complete breakthrough every 0.3 km; 42% of

complete breakthroughs were from stream crossings, 27% from reactivation of legacy agricultural gullies, and 24% from harvest related soil disturbances

Morris et al. (2015)	Piedmont (Virginia)	Academia	Effectiveness of stream crossing BMPs for sediment control (bridge, culvert, ford); three treatments: (1) minimal BMP erosion control (low), (2) BMP erosion control recommended by the Virginia BMP Manual (medium), and (3) erosion control exceeding the Virginia BMP Manual recommendations (high)	Found that the culvert stream crossing produced double the sediment concentration (2.9 g/L) than the ford (1.4 g/L) and ten times more than the bridge (0.2 g/L); current Virginia BMPs were effective in reducing sedimentation
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2.5 Northern States

BMP effectiveness studies in the northern US take place primarily in the northeastern and lake state regions (Figure 2). Effectiveness studies across the Northern states cover a range of different physiographic regions. Twenty effectiveness studies from 1963 to 2014 were reviewed by organization conducting the study: academia (6), federal (6), state (6), and non-profit (2) (Table 2).

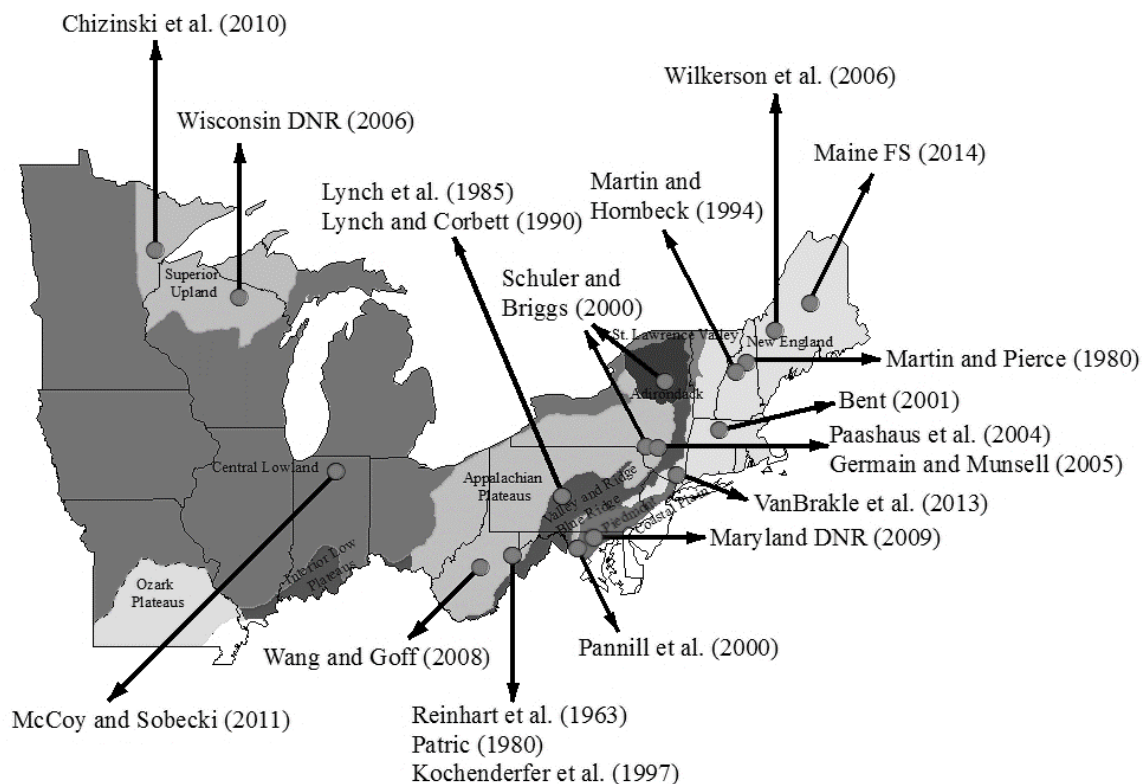


Figure 2. Reviewed BMP effectiveness studies by state and physiographic region for the northern United States. Locations were determined from the studies as well as Schilling and Ice (2012).

2.5.1 Academia

2.5.1.1 Water Quality

Lynch et al. (1985) studied BMPs for controlling NPSP in the Ridge and Valley physiographic region of central Pennsylvania. Their study included three treatment watersheds: (1) commercial clearcut, (2) clearcut with herbicide, and (3) control. The authors evaluated stream chemistry, turbidity, sediment concentrations, water temperature, and nutrient concentrations. Lynch et al. (1985) found small increases in turbidity and sediment concentrations and suggested these increases were due to erosion caused by windblown trees located along the intermittent stream channel. The authors concluded that BMPs were effective and that a buffer strip might have helped reduce windblown trees along the stream channel.

Lynch and Corbertt (1990) evaluated the effectiveness of BMPs from long-term (15-year) streamflow and water quality data in the Ridge and Valley of central Pennsylvania. Their study was a paired watershed on the Leading Ridge Experimental Watershed Research Unit which consisted of a 303 acre control watershed and a 257 acre treatment watershed (110 ac clearcut). The authors found significant, however relatively small, increases at two years post-harvest in nitrate and potassium concentrations, stream temperature, and turbidity. The authors also found that by year four post-harvest, water yields returned to pre-harvest levels. Lynch and Corbertt (1990) concluded that BMPs were effective due to no serious alterations of water quality and suggested buffer strips on intermittent streams, increases in buffer strip width, and post-harvest site inspections.

Passhaus et al. (2004) sampled macroinvertebrates populations in ephemeral streams pre-harvest and post-harvest. Their study was a paired watershed (treatment and control) study in the Catskills of southern New York. The treatment watershed was thinned (60% of the basal area).

The authors did not find any significant impacts on macroinvertebrate populations from the thinning operation.

Chizinski et al. (2010) evaluated the response of macroinvertebrate and fish communities to partial harvesting stream buffers on four small streams located in the Superior Upland physiographic region of northern Minnesota. Their study included three treatments: (1) control, (2) clearcut with no harvesting in stream buffer, and (3) clearcut with harvesting within stream buffer. The authors conducted sampling one year pre-harvest and then for three years post-harvest. Chizinski et al. (2010) found few effects in partial harvesting stream buffers for macroinvertebrate communities and did not find any significant changes in fish communities. They concluded that timber can be harvested to a certain degree in stream buffers.

2.5.1.2 BMP Implementation

Schuler and Briggs (2000) examined the application and effectiveness of New York BMPs. Their study evaluated 42 BMP guidelines for roads, landings, skid trails, equipment, and buffer strips on 114 harvested sites in the Catskills (61) and Adirondacks (53). The authors reported BMP application was 78% for roads, 87% for landings, 59% for skid trails, 88% for equipment, and 73% for buffer strips. Applying BMPs decreased sediment movement, while failure to properly apply BMPs resulted in lower effectiveness measures.

Germain and Munsell (2005) assessed surface area disturbance from forest roads, skid trails, and landings (harvest access systems) in the Catskills of New York. The authors mailed a survey to landowners who conducted recent timber harvesting and visited sites where permission was granted. The authors used a modified BMP site evaluation from Schuler and Briggs (2000). Their site evaluation included surface area disturbance measurements of landings, roads, skid

trails, stream crossings (roads and skid trails) on 43 sites. Germain and Munsell (2005) found low surface area disturbance does not always result in high BMP implementation.

2.5.2 State

Pannill et al. (2000) evaluated the effectiveness of Maryland's BMPs on a paired watershed study that incorporated a control watershed and a partially harvested watershed. The authors sampled TSS, stormflow, stream temperature, and macroinvertebrates and found no significant differences between the pre-harvest period and post-harvest treatment. They concluded that properly implemented BMPs will help protect stream water quality, biology, and habitat.

Wisconsin officially published their first BMP manual in 1995 when their water quality program was developed. Wisconsin DNR (2006) assessed the first ten years of their water quality program (1995-2005). They found the average BMP compliance was 83% over that time period and that BMP effectiveness was 99% when the adequate BMPs were applied. Wisconsin DNR (2006) reported that when BMPs were not followed, water quality was impacted 71% of the time.

Wang and Goff (2008) assessed the application and effectiveness of West Virginia BMPs. The authors selected a sample of 33 harvested sites with SMZs from a previous survey of 116 sites. They evaluated 27 West Virginia BMP guidelines for forest roads, skid trails, landings, and SMZs and found average effectiveness was 80% with an average application of 85%. The authors also found industrial land or land that involved a professional forester resulted in increased application and effectiveness scores.

The Maryland DNR (2009) evaluated implementation and effectiveness of Maryland's BMPs from 2004 to 2005. Their study assessed BMPs on 75 forest harvested sites throughout the

state. The overall BMP implementation was 81% for all 75 sites and 81% for sites that had water present. They found that BMPs were 77% effective in protecting water quality from sediment delivery. The Maryland DNR (2009) also reported that 19% of sites delivered measurable sediment to waterways.

McCoy and Sobecki (2011) conducted a review of Indiana forestry BMP monitoring from 1996 to 2011. Indiana formed their first BMP guidelines in 1995 with their first monitoring conducted in 1996. Over their 15 year review, 671 sites were monitored for BMP implementation and effectiveness with an average BMP implementation rate of 86% and an average effectiveness rate of 93%. Stream crossing BMPs had the lowest rating for both effectiveness (79%) and implementation (74%). The authors concluded that with a high overall effectiveness rating, impacts to water quality from forest operations in Indiana is small.

The Maine FS (2014) assessed the implementation and effectiveness of Maine's forestry BMPs in protecting water quality. Their study consisted of monitoring 101 harvested sites. Forestry BMPs were 91% effective in protecting water quality from sediment. Stream crossings and approaches had the proper BMPs on 83% of the crossings monitored. The Maine FS (2014) stated that BMPs prevent sedimentation when implemented properly.

2.5.3 Federal

Reinhart et al. (1963) evaluated the effects of timber harvesting on streamflow in West Virginia. Their study started with pre-harvest measurements of water quality for six years on five watersheds. After the six year pre-harvest measurement period, four of the watersheds were harvested with different treatments (commercial clearcut, diameter limit cut, extensive selection, and intensive selection) and water quality was sampled again. The authors found that harvesting timber can increase stormflow; careless logging causes high turbidity levels; poor skid trails

affect water quality; and the highest impact to water quality was immediately after the timber harvest.

Martin and Pierce (1980) evaluated the effects of clearcutting on nitrate and calcium in streams on the White Mountain National Forest in New Hampshire. Their study included: (1) water quality sampling of nine streams from watersheds that were completely clearcut, (2) seven streams from partially clearcut watersheds, and (3) seven streams from uncut watersheds. The authors did not sample the watersheds pre-harvest. The authors found that leaving buffers around streams and not clearcutting entire watersheds can reduce the magnitude and duration of nitrate and calcium increases.

Patric (1980) studied the effects of harvesting on forest soils and water relations on the Fernow Experimental Forest in West Virginia. His study was on a 34.7 ha watershed that evaluated different harvesting treatments for the previous 20 years. The first treatment for this study included clearcutting 31.7 ha of the watershed leaving a 20 m stream buffer strip on each side of the stream. The second treatment harvested the buffer strip. The author found that sediment concentrations in stormflow had small increases for the clearcut with a buffer strips but these small increases had little effect on water quality. Patric (1980) did find when removing the buffer strip, water yield and stream temperature increased, which were not affected when the buffer strip was left.

Martin and Hornbeck (1994) compared sediment yields and stream turbidity levels on harvested and no harvest watersheds. Their study was on the Hubbard Brook Experimental Forest in New Hampshire and consisted of three no harvest watersheds (reference) and four harvested watersheds (clear-felled, strip-cut, mechanized whole-tree clearcut, and clearcut). The authors evaluated sediment yield and turbidity on all the watersheds, however the clearcut

watershed did not include sediment yield measurements. Martin and Hornbeck (1994) found that sediment yields increased from logging but did not find significant differences that affected water quality. They concluded that BMPs will help control erosion and sedimentation.

Kochenderfer et al. (1997) evaluated the effectiveness of West Virginia BMPs on a 39 ha watershed that was harvested to a 35.5 cm stump diameter limit. A John Deere 850 bulldozer was used to create roads and skid trails and a wheeled skidder and tri-axle truck for primary and secondary hauling. Harvesting resulted in significant increases in total stormflow and peakflows during the growing season. However, the dormant season did not result in any significant increases. They also found that suspended sediments doubled when the watershed was harvested and that sediment exports returned to pre-treatment levels three years post-harvest. Kochenderfer et al. (1997) concluded that West Virginia BMPs applied on the harvested watershed reduced any critical impacts to water quality.

Bent (2001) assessed the effects of timber harvesting and herbicide applications on runoff and ground water recharge in two drainage basins of central Massachusetts. Cadwell Creek and Dickey Brook basins were examined and each included a treatment and control section. After harvesting, the basal area was reduced by 34% and 32% in the Cadwell Creek basin and Dickey Brook basin, respectively. The Cadwell Creek basin resulted in increased streamflow, direct runoff, and ground water recharge for six years post-harvest, while the Dickey Brook basin only had increases for one year post-harvest. Bent (2001) suspected that the large stormflow increases in Cadwell basin were caused by the location of harvest treatments and riparian zone.

2.5.4 Non-Profit

Wilkerson et al. (2006) evaluated the effectiveness of stream buffers on headwater stream temperature in western Maine. This study was conducted by Manomet. Five treatments on 15

streams included: (1) clearcutting with no buffer, (2) clearcutting with partially harvesting 11 m buffer, (3) clearcutting with partially harvesting 23 m buffer, (4) partial harvest with no defined buffer, and (5) control. The authors found that after harvesting, the no buffer streams had the highest increases in stream temperature. Additionally, both partially harvested 11 m and 23 m buffer treatments were sufficient in protecting stream temperature increases in headwater streams.

VanBrakle et al. (2013) examined if forest management plans increase BMP implementation on family forests in the New York City watershed. This study was conducted by the Watershed Agricultural Council. The authors evaluated forestry BMPs for forest roads, skid trails, landings, stream crossings (haul roads and skid trails), and water diversion. The only BMPs evaluated that resulted in significantly higher implementation scores were skid trails and forest roads. The authors suggested that possibly providing more programs to logger training and timber sale contract education would help increase BMP implementation.

Table 2. Summary of forestry BMP effectiveness studies for the northern United States by investigator(s), location, evaluations and treatments, and major conclusions.

Investigators	Region/ Location	Study conducted by	Evaluations/treatments	Major conclusions
Reinhart et al. (1963)	West Virginia	Federal	Effects of timber harvesting practices on streamflow; treatments included: commercial clearcutting, diameter limit cutting, extensive selection management, and intensive selection	Timber harvesting increases storm flow; water quality is affected due to poor skid trails and logging; unplanned skid trails caused water quality issues
Martin and Pierce (1980)	New Hampshire	Federal	Effects of clearcutting on nitrate and calcium in streams; treatments included: 9 clearcut watersheds, 7 partially clearcut watersheds, and 7 uncut watersheds	Clearcutting less than entire watersheds and leaving buffers around streams reduced the magnitude and duration of nitrate and calcium increases
Patric (1980)	North central West Virginia	Federal	Effects of harvesting on forest soil and water relations; two treatments: (1) clearcut with 20 m buffer on both sides of the stream and (2) harvesting 20 m buffer	Treatment 1 resulted in no effect on storm flow and stream temperature, however water yield increased 38% the first year after harvest, sediment concentrations were low due to buffer and management of logging roads; treatment 2 increased water yield an additional 9% and stream temperature 7.8°C

Lynch et al. (1985)	Central Pennsylvania	Academia	BMPs for controlling nonpoint source pollution; treatments included: (1) commercial clearcut, (2) clearcut with herbicide, and (3) control; BMPs were implemented on clearcuts; sampled water quality, turbidity, water temperature, and nutrient concentrations for two years after harvest	BMPs were effective in controlling nonpoint source pollution following logging in central Pennsylvania; slight increases in turbidity and sedimentation could have been from windblown trees near an intermittent stream channel and that buffer strips would have helped reduce erosion
Lynch and Corbett (1990)	Ridge and Valley (central Pennsylvania)	Academia	Long-term (15-year) evaluation of BMPs for controlling nonpoint source pollution; paired watershed study included a control watershed (303 ac) and a 110 ac commercial clearcut watershed (257 ac); evaluated changes in water quality and quantity	Found small significant increase in nitrate and potassium concentrations and temperature and turbidity levels for first two years following the harvest; BMPs applied were effective because there were no serious changes in water quality; recommendations: conduct post-harvest inspections, increase buffer zone width, and include buffer zone on intermittent streams
Martin and Hornbeck (1994)	Central New Hampshire	Federal	Compared sediment yields and stream turbidities on harvested and un-harvested watersheds; the study consisted of three control watersheds and four treatment watersheds; watershed treatments included: (1) clear-felled, (2) strip-cut (strips 25 m), (3) mechanized whole tree clearcut, and (4) clearcut (no sediment data)	Watersheds were harvested before state published BMPs; however logging did follow state BMPs for erosion control and sedimentation; sediment yields were not greatly affected from harvesting and skidding

Kochenderfer et al. (1997)	Allegheny Plateau (West Virginia)	Federal	Effectiveness of West Virginia BMPs on a 39 ha watershed that was harvested to a 35.5 cm stump diameter; John Deere 850 bulldozer used for roads and skid trails, wheeled skidders used for skidding, and tri-axle truck for hauling	Found that BMPs applied to the site were effective for reducing impacts to soil and water quality
Pannill et al. (2000)	Maryland	State	Effectiveness of forestry BMPs in protecting water quality on a small watershed following forest harvesting; control watershed treatment and a timber harvested watershed that adhered to BMPs	BMPs implemented were effective in protecting stream water quality, biology, and habitat
Schuler and Briggs (2000)	Catskill and Adirondack Regions (New York)	Academia	Application and effectiveness of 42 forestry BMPs on 61 harvested sites in Catskill Region and 53 harvested sites in the Adirondack Region; used evidence of sediment movement to define effectiveness	Good application of BMPs decreased sediment movement which provided protection for surface waters; BMPs were effective; lower effectiveness of BMPs were due to imperfectly applied BMPs
Bent (2001)	Central Massachusetts	Federal	Effects of timber harvesting and herbicide application on runoff and ground water recharge for two separate paired drainage basins (Cadwell Creek and Dickey Brook)	Cadwell Creek basin resulted in increased streamflow, direct runoff, and ground water recharge for six years following the treatments and increased base flow for 2.5 years; Dickey Brook basin only had increased levels for one year following harvest; Dickey Brook was less influenced by the treatments because of location of riparian zones

Paashaus et al. (2004)	Southern New York	Academia	Impacts on macroinvertebrates in ephemeral streams from partial timber harvesting; bio-monitoring conducted on paired watersheds (control and treatment)	Macroinvertebrates in ephemeral streams were not impacted from partial timber harvesting
Germain and Munsell (2005)	Catskills (New York)	Academia	Assessed surface area disturbance by harvest access system; 43 nonindustrial private forest landowners northern hardwood harvested sites were evaluated	Found that high BMP implementation was positively related to the surface area (%) disturbed; harvested sites with low disturbed area do not always equal high BMP implementation
Wilkerson et al. (2006)	Western Maine	Non-profit	Effectiveness of different buffer widths for protecting headwater stream temperature following timber harvests; five treatments: (1) clearcut with no buffer, (2) clearcut with 11 m partially harvest buffer, (3) clearcut with 23 m partially harvested buffer, (4) partial cut with no defined buffer, and (5) control	Streams without buffers had the highest (significant) increase in weekly maximum temperatures; streams with the 11 m buffer showed minor increases but no significant increases; buffers consisting of at least an 11 m buffer were sufficient in protecting water temperature in small headwater streams
Wisconsin DNR (2006)	Wisconsin	State	Evaluated state forestry BMPs from 1995-2005	State BMP effectiveness is high when BMPs are applied correctly; when BMPs were not applied, impacts to water quality were found 71% of the time; found that BMPs were effective 99% of the time

Wang and Goff (2008)	West Virginia	State	Effectiveness of forestry BMPs; randomly selected 33 of 116 sites from a previous state assessment that evaluated a timber harvest with an SMZ; Used the West Virginia BMP manual to evaluate haul roads, skid trails, landings, and SMZs	Found that BMP application and effectiveness rates were higher on industrial land or with the involvement of a professional forester
Maryland DNR (2009)	Maryland	State	Forestry BMP implementation and effectiveness for protecting water resources in the state; evaluated 75 forest harvesting sites (2004-2005)	BMPs were 77% effective in preventing sediment delivery; 4% of sites saw trace amounts of sediment; 19% of the sites had measureable amounts of sediment reaching water
Chizinski et al. (2010)	Northern Minnesota	Academia	Influence of partial timber harvests in riparian buffers on macroinvertebrate and fish communities in small streams; sampled benthic macroinvertebrate and fish one year prior to harvest and for three years following the harvest	Found few effects related to the harvest that affected macroinvertebrate communities and no significant changes in fish communities; timber harvesting to a certain degree in riparian buffers does not affect macroinvertebrate and fish communities in northern Minnesota
McCoy and Sobecki (2011)	Indiana	State	Comprehensive review of Indiana BMP monitoring results from 1996-2011; Indiana Division of Forestry monitored 671 sites in that time frame	BMP effectiveness rate was 93%; concluded that there has been little impact on water quality because of the high effectiveness rate (if BMPs are applied properly).

VanBrakle et al. (2013)	New York	Non-profit	Examined if forest management plans increase BMP implementation on family forests in the New York City watershed; evaluated forest roads, landings, forest stream crossings, skid trails, skid trail stream crossings, and water diversion methods on private forestland	Minimal difference in BMP implementation between landowners that had management plans and landowners that did not have management plans; suggest that potentially moving funds from management plans to logger training and timber sale contract education programs
Maine FS (2014)	Maine	State	Assessed BMP effectiveness of Maine's BMPs; evaluated sites for sediment inputs into waterways	Found that 91% of the time there was no sediment entering waterways; BMPs are effective in preventing sedimentation when implemented properly

2.6 Western States

BMP effectiveness studies in the Western US focus primarily on the Pacific Border physiographic region where forest operations are most prevalent (Figure 3). Several effectiveness studies used paired watershed experiments that included multiple studies, Alsea Watershed (Oregon Coast Range), Caspar Creek Experimental Watershed (northwestern California), and Mica Creek Experimental Watershed (northern Idaho). Thirty-one BMP effectiveness studies from 1978 to 2015 were reviewed by the organization whom conducted the study: academia (9), federal (12), state (5), industry (2), private (1), and non-profit (2) (Table 3).

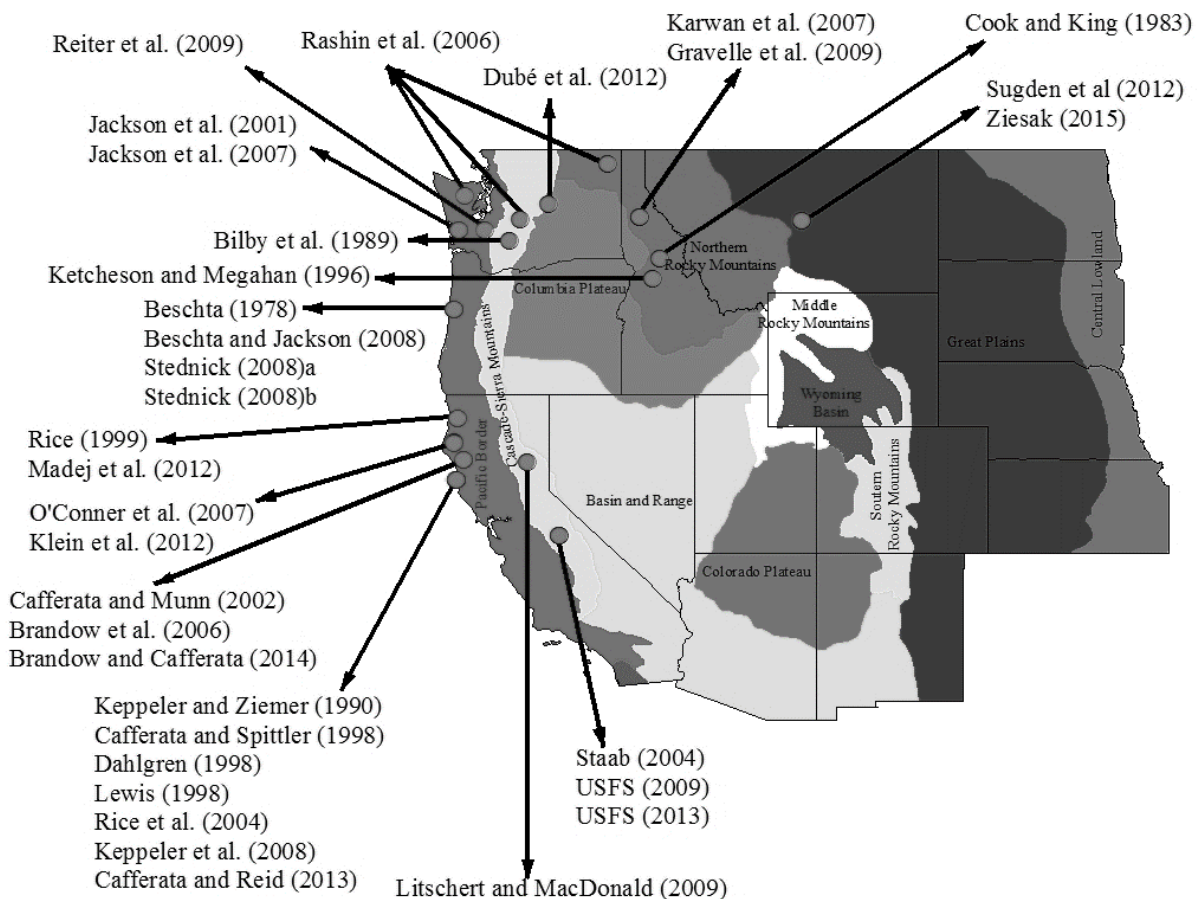


Figure 3. Reviewed BMP effectiveness studies by state and physiographic region for the western United States. Locations were determined from the studies as well as Schilling and Ice (2012).

2.6.1 Academia

2.6.1.1 Sediment Production

Beschta (1978) assessed the long-term patterns of sediment production from road construction and logging on the Alsea Watershed in Oregon. This paired watershed study included three treatment watersheds: (1) control (Flynn Creek), (2) clearcut, slash burning, and no stream buffers (Needle Branch), and (3) patch-cut, roads, and burned (Deer Creek). The author found that road construction and road failures in Deer Creek watershed significantly increased sediment yield for three years post-treatment. The Needle Branch watershed resulted in 5 years of increased sediment yields due to erosion from the slash burn and no stream buffer.

Karwan et al. (2007) evaluated suspended sediment loads from timber harvesting on the Mica Creek Experimental Forest in northern Idaho. The authors used a paired watershed method and monitored seven stream monitoring flumes for TSS from 1991-1997 (pre-harvest and pre-road construction/improvement), 1998-2001 (post-road construction/improvement), and 2001-2004 (post-harvest). Treatments for forest roads included constructing new roads and improving existing roads, while treatments for harvesting included: (1) 50% commercial clearcut then broadcast, burned, and replanted, (2) 50% partial harvest, and (3) control. Idaho's Forest Practice Act (FPA) guidelines were followed. No significant differences in sediment loads among forest road treatments in both harvested watersheds were detected. However, significantly higher monthly sediment loads were reported within the commercially clearcut watershed after the harvest, but significant differences dissipated after one year.

Beschta and Jackson (2008) summarized effects of road building, logging, and slash burning on sediment production from past studies in the Alsea Watershed. Authors reported that management practices such as minimizing road construction, clearcutting less area, applying

stream buffers, and low intensity slash burns can reduce sediment production. The authors concluded that paired watershed studies similar to Alsea Watershed experiments are important for demonstrating different forest practices and their effects on water quality.

2.6.1.2 Stream Buffers

Jackson et al. (2001) assessed impacts of timber harvesting on 15 headwater streams in Washington's Coast Range. The authors evaluated stream channel habitat, distributions of bed material, and temperature. The treatments applied included: (1) no harvest (reference), (2) clearcut with un-thinned buffer, (3) clearcut with partial buffer, and (4) clearcut with buffer consisting of non-merchantable trees, and (5) clearcut with no buffer. The authors found treatments with a stream buffer did not alter particle size distributions and habitat distributions when compared to the no harvest treatments.

Jackson et al. (2007) built onto the study conducted by Jackson et al. (2001) by evaluating abiotic and biotic responses to timber harvesting. The authors sampled geomorphology, macroinvertebrates, and amphibians before and following timber harvesting. Jackson et al. (2007) found that clearcutting with no buffers resulted in negative short-lived effects for some amphibian species. The authors also found that macroinvertebrate communities remained in flux for both the buffered and no buffer streams and changes in communities were due to additional organic matter from the harvest.

2.6.1.3 Water Yield and Water Quality

Stednick (2008a) assessed long-term streamflow changes after timber harvesting on the Alsea Watershed. The author plotted differences in measured annual water yield and predicted streamflows for the two treatment watersheds (Deer Creek and Needle Branch). The author found that low flow metrics and peak flows were not significantly different than pre-treatment levels and annual water yield increases in the Needle Branch watershed were not present after 31

years. The Deer Creek watershed had additional timber harvesting treatments and did not result in any significant differences in flow metrics. Stednick (2008a) concluded that BMPs were effective in not changing streamflow metrics.

Stednick (2008b) assessed the long-term water quality changes after timber harvesting on the Alsea Watershed. The author found significantly lower nitrate-nitrogen concentrations after timber harvesting in the Needle Branch (no buffer treatment) watershed when compared to the control (Flynn Creek) and Deer Creek (patch-cut treatment) watersheds. However, there was a significant increase in nitrate-nitrogen fluxes when compared to pre-treatment water quality measurements. The Deer Creek watershed did not have any significant water quality changes after multiple timber harvests. The author suggested this was caused by BMPs that were applied on the watershed.

Gravelle et al. (2009) evaluated timber harvesting impacts on aquatic macroinvertebrates in the Mica Creek Experimental Watershed in northern Idaho. Their study consisted of three measurement periods over four years each: (1) calibration, (2) post roads, and (3) post-harvest. The authors sampled feeding groups, densities, taxa richness, diversity, and sediment tolerance indices. Additionally, they assessed three main macroinvertebrate taxa (mayflies, stoneflies, and caddis flies). Gravelle et al. (2009) did not find any changes in macroinvertebrate communities from road construction and timber harvesting and suggested it was due to BMPs being followed.

2.6.2 Federal

2.6.2.1 Sediment Production

Cook and King (1983) assessed the erosion control effectiveness of filter windrows on fill slopes on the Nez Perce National Forest in Idaho. The authors evaluated filter windrows (sediment barriers) of slash on newly constructed roads near stream crossings to determine their

effectiveness of reducing fill material from entering streams. The authors found that the filter windrows trapped 75 to 95% of sediment and concluded that they are an inexpensive effective method of preventing erosion from entering streams.

Ketcheson and Megahan (1996) evaluated sediment production and sediment transport downslope caused by forest roads in granitic watersheds of southwestern Idaho. The authors measured sediment deposits on constructed roads for four years. They found that 70% of the total erosion occurred during the initial year following road construction. Ketcheson and Megahan reported that erosion control treatments reduced erosion.

Cafferata and Spittler (1998) compared harvesting impacts in the Casper Creek watershed from the 1970's to the 1990's. Two treatment watersheds (North Fork and South Fork) were compared. South Fork roads were constructed in the 1960's and located near stream channels. This watershed was selectively harvested using tractors in the 1970's. The North Fork was cable logged (clearcut) between 1985 and 1991 and roads were located away from stream channels (on ridges). The South Fork had higher sediment yield and erosion due to the harvest. The authors suspected that much of the sediment production was produced by legacy roads, which were constructed prior to the FPA.

Lewis (1998) assessed erosion and suspended sediment transport from logging in the Casper Creek watershed. The author measured suspended sediment, turbidity, and erosion and estimated suspended sediment load and total sediment load on timber harvests conducted in the North Fork (harvested with 1990 Forest Practice Rules) and South Fork (harvested before 1990 Forest Practice Rules) watersheds. Lewis (1998) reported $1,475 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and $2,877 \text{ kg ha}^{-1} \text{ yr}^{-1}$ after road construction and harvesting for the South Fork watershed. No effect was reported in the North Fork watershed for sediment loads.

Madej et al (2012) assessed changes in land use practices on sediment loads in the Panther Creek basin of the northwestern California. The author's evaluated timber harvesting methods and road designs. Over half of the watershed was clearcut from harvests occurring between 1978 and 2008 with some thinning and selection harvesting also occurring. The authors stated that roads were upgraded and some decommissioned between 2000 and 2009. Riparian buffers were left on streams since 1984. Madej et al. (2012) found that the harvested area had a higher sediment yield compared to the control (un-harvested). Most sediment issues were caused from landslides on forest roads and landings. However, suspended sediment concentrations decreased due to improved management practices.

O'Conner et al. (2007) assessed the effects of recent harvests and legacy management techniques on sediment yield from first order streams in northwestern California. The study had three treatments: (1) clearcut with a Habitat Conservation Plan (HCP), (2) clearcut without a HCP, and (3) control. The authors used sediment basins to measure trapped sediment. O'Conner et al. (2007) did not find any significant differences between sites, but noted that HCP sites had lower sedimentation when compared to sites without a HCP.

2.6.2.2 Water Yield and Water Quality

Keppeler and Ziemer (1990) assessed harvesting impacts on streamflow for 21 years on the Casper Creek watershed in northwestern California. Their study included a control (North Fork; prior to harvesting) and selective harvest with new road construction treatment (South Fork). The authors measured water yield, volume, timing, and duration of low flows. Keppeler and Ziemer (1990) found that the greatest increase in water yield was the first year after harvest. Water yield decreased irregularly in the following years.

Dahlgren (1998) studied the effects of timber harvesting on stream water quality and nitrogen cycling in the Casper Creek watershed. The author collected stream water quality samples from both control and treatment (clearcut) watersheds and completed a nutrient cycling study. He found that nitrate concentrations were higher in clearcut and decreased downstream in higher order streams. The author also reported a $1.8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ loss post-harvest and less than $0.4 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ three years post-harvest. The control watershed for the same period resulted in a nitrogen loss less than $0.1 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. Dahlgren noted that the nitrogen loss was small and accredited the small loss to the redwood and Douglas-fir forest ecosystem.

Keppeler et al. (2008) evaluated the long-term patterns of hydrologic response post-harvesting in the Casper Creek watershed. The authors found that both the North Fork and South Fork had similar water yield, peak flows, and low flows. Low flows returned to pre-harvest conditions faster for selective logging. Keppeler et al. (2008) also found that sediment loads recovered quickly after harvesting on both watersheds. However, 10-20 years post-harvest, sediment loads increased due to road failures on the South Fork or pre-commercial thinning on the North Fork.

Elliot (2010) evaluated the watershed processes from forest biomass harvesting in the western United States. The author implemented BMPs to reduce impacts of biomass harvesting and recommended two general guidelines: (1) minimize disturbances to the duff layer and soil and (2) minimize and maintain roads. Elliot (2010) stated that increased road traffic and compacting or disturbing the soil can increase erosion and runoff.

Klein et al. (2012) assessed turbidity levels from winter runoff on 28 coastal watersheds in northern California. Study watersheds ranged from un-harvested redwood forests to commercial harvesting. The authors found that the rate of timber harvesting and watershed

drainage areas can affect water quality. They stated that BMPs reduce erosion, but were not always implemented properly. The authors also noted that in large watersheds harvested over a short period of time can impact water quality.

USFS (2013) evaluated their Pacific Southwest Region BMP program from 2008 to 2010 to determine BMP implementation and effectiveness. Similar evaluations were conducted in the past by Staab (2004) and USFS (2009). BMP inspections were conducted on 2,237 randomly selected sites. Reported BMP implementation was 91% with an effectiveness of 80%. Effectiveness was low due to water quality being affected at streams on roughly 12% of the sites. The USFS (2013) found that BMPs for timber harvesting, fuels treatments, and vegetation management was effective, however, BMPs for roads, range management, recreation, and mining were not as effective. The USFS (2013) also noted that effectiveness can be increased by improving erosion control plans and wet-weather standards.

2.6.3 State

2.6.3.1 Water Quality

Litschert and MacDonald (2009) assessed the frequency and characteristics of sediment delivery pathways on harvested sites on National Forest land in the Sierra Nevada and Cascade mountains of California. The authors evaluated 200 harvested sites that included SMZs and used the term ‘features’ to describe eroded areas of the harvest. They found 19 features on 200 sites that were caused by rills or gullies (15) and sediment plumes (4). Sixteen of the features started from skid trails of which five features connected to streams. The authors also found that feature length was significantly related to hillslope gradient, mean annual precipitation, and elevation. Litschert and MacDonald (2009) suggested that sediment delivery to streams can be reduced by:

(1) locate skid trails away from streams, (2) use waterbars with high surface roughness, and (3) close skid trails.

Cafferata and Reid (2013) conducted a review of the long-term (50-year) watershed research conducted at the Casper Creek watershed. The authors described the history and treatments applied on both North and South Fork watersheds. They also provided key lessons learned and findings from the past research. Some of the past research consisted of measuring peak flows, water yield, hydrology, erosion, stream temperature, and sediment yields. Cafferata and Reid (2013) noted that results and monitoring methods from the Casper Creek watershed were used to address forestry issues in California and throughout the world. The authors also stated that research is continuing on the watershed.

2.6.3.2 Implementation and Effectiveness

Dubé et al. (2010) conducted a study assessing the Washington road sub-basin scale effectiveness monitoring program. The objectives of this program were to determine if the new Forest Fish Reports (FFRs) for forest roads improved protection of runoff and sediment delivery and how many roads met FFR performance targets. The authors evaluated characteristics of forest roads over 60 sample units across the state of Washington (each unit was four square miles). They found 62% of the units met FFR targets for hydrology performance. FFR targets for sediment protection were met in 88% of the units.

Sugden et al. (2012) assessed Montana's forestry BMP program for the past 20 years. The authors demonstrated the positive progression of Montana's BMP using past BMP audit reports. In 1990, BMP implementation was 78% and increased to 97% 20 years later. Water quality infractions per harvest site decreased from eight in 1990 to less than 1 in 2010.

Brandow and Cafferata (2014) evaluated California's Forest Practice Rules (FPR) implementation and effectiveness monitoring program from 2008 to 2013. This study was based off similar earlier studies conducted by Cafferata and Munn (2002) and Brandow et al. (2006). The purpose of this study was to determine rate of implementation of FPRs and effectiveness of FPRs in protecting water quality. The authors selected sites from California's Coastal, Cascade, and Sierra Regions. Evaluations of sites indicated that implementation of FPRs were high and FRPs were effective in preventing sedimentation. Brandow and Cafferata found that water courses and lake protection zones, roads, and stream crossings had 90% implementation or higher depending on FPR. The authors suggested improvements to be made for stream crossing design, construction and maintenance, and closure.

Ziesak (2015) reviewed 42 sites for BMP application and effectiveness for Montana's BMP monitoring study in 2014. BMP application (implementation) was 97% and BMP effectiveness in protecting water quality was 98%. Like previous monitoring reports from Montana, road maintenance and road surface drainage were the main impacts on water quality.

2.6.4 Industry

Bilby et al. (1989) assessed road surface sediment production on five road segments in two southwestern Washington watersheds. Two heavily trafficked roads located on valley-bottoms were built in the 1950s. Three haul roads, built between 1968 and 1974, were located mid-slope. Suspended sediments were analyzed on the sites. The authors found that sediment entered first and second order streams 34% of the time and would temporary retain sediments from reaching larger streams. Bilby et al. (1989) stated that steep roads that are heavily used and drain directly into large streams will have a higher potential of impacting water quality.

Reiter et al. (2009) assessed temporal and spatial turbidity patterns over 30 years in the Pacific Northwest of Washington. The authors used long-term data on stream discharge, suspended sediment, turbidity, and water and air temperature to determine impacts of sediment control practices on water quality. Data was collected at four permanent monitoring sites throughout the study watershed. Turbidity declined at all four monitoring sites. The authors found that turbidity levels when evaluated for the entire watershed declined, even during active forest operations. Reiter et al. (2009) reported that declined sediment production was caused by increased attention to forest practices for roads.

2.6.5 Private

Rice (1999) evaluated erosion from logging roads on the Redwood Creek watershed in northwestern California. The author stated that the roads were installed between 1950 and 1958 for logging and were maintained to standards of the past decade. His sample design consisted of 100 sites within the 180 km of roads in the middle of the watershed. The author estimated the mean erosion rate to be $177 \text{ m}^3 \text{ km}^{-1}$ from 1980 to 1997. The main source of erosion was from the road cut banks. Rice (1999) noted that changes in FPRs (proper placement of culverts and sizing of culverts) reduced erosion on logging roads.

2.6.6 Non-Profit

Rice et al. (2004) conducted a review of the effects of forest management on erosion, sediment, and runoff on the Caspar Creek watershed. The authors reported sediment loads were higher before the 1973 FPA for selective logging and road construction. They also reported smaller but significant increases in sediment from clearcutting following the 1990 FPA.

Rashin et al. (2006) assessed the effectiveness of BMPs on water quality impacts due to sediment delivery in Washington. They evaluated BMPs for first two years post-harvest on 26

timber harvested sites between 1992 and 1995. The authors used a weighted approach to determine BMP effectiveness based on sediment delivery, disturbance of stream channels, and aquatic habitat conditions. They found stream buffers were effective at preventing sediment delivery. The authors also listed several factors that influenced BMP effectiveness: (1) equipment disturbance near streams, (2) use of stream buffers, (3) use of proper harvesting practices to minimize stream channel disturbance, and (4) time of year.

Table 3. Summary of forestry BMP effectiveness studies for the western United States by investigator(s), location, evaluations and treatments, and major conclusions.

Investigators	Region/ Location	Study conducted by	Evaluations/treatments	Major conclusions
Beschta (1978)	Coast Range (Oregon)	Academia	Long-term patterns of sediment production following road construction and logging on the Alsea Watershed; paired watershed study: (1) control watershed (Flynn Creek), (2) clearcut, slash burning, and no stream buffer strips watershed (Needle Branch), and (3) patch-cut, roads, and burned watershed (Deer Creek)	Deer Creek treatment resulted in significant increases of sediment yield for three years following treatment due to road construction and road associated failures; Needle Creek treatment resulted in increased sediment yield for five years following treatment with the first year resulting in a fivefold increase primarily due to a severe slash fire and logging along the stream channel
Cook and King (1983)	Idaho	Federal	Construction cost and erosion control effectiveness of filter windrows on fill slopes; monitored sediment barriers of slash on newly constructed roads near stream crossings	Estimated sediment trapping efficiency was between 75% and 85%; concluded that filter windrows of slash were an inexpensive and effective way to prevent erosion
Bilby et al. (1989)	Southwestern Washington	Industry	Fate of road-surface sediment in forested watersheds; used new data and data from previous road studies	Roads with steep gradients, heavily used, and drain directly into larger streams have the greatest potential to impact streams; problems with forest roads can be reduced by applying appropriate management procedures

Keppeler and Ziemer (1990)	Northwestern California	Federal	Logging effects on streamflow for a 21 year period on the Casper Creek Experimental Watershed; evaluated selective tractor harvesting on volume, timing, and duration of low flows and annual water yield	Greatest increase in water yield was during the initial year following the logging operation; water yields decreased irregularly the following years
Ketcheson and Megahan (1996)	Southwestern Idaho	Federal	Sediment production and downslope sediment transport from forest roads in granitic watersheds; measured annual downslope deposition of granitic sediments from forest roads; treatments included different erosion control practices	Found that 70% of the sediment deposited on the slopes occurred during the first year after construction; standard erosion control practices for road construction resulted in an average annual erosion rate of $50.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ and intensive erosion control practices for road construction resulted in an average erosion rate of $17.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (reduced erosion by 66%)
Cafferata and Spittler (1998)	Northwestern California	Federal	Compared logging impacts from the 1970s to the 1990s in the Casper Creek Experimental Watershed	Legacy roads that were constructed before the FPA continue to affect the South Fork watershed; concluded that legacy roads need to be properly closed under the new FPRs
Dahlgren (1998)	Northwestern California	Federal	Effects of forest harvesting on stream water quality and nitrogen cycling in the Casper Creek watershed; sampled water quality (clearcut vs. un-harvested); detailed nutrient cycling study	Found higher concentrations of stream water nitrate in the clearcut watershed; nutrient losses in stream water in redwood-Douglas-fir forests after harvest were small compared to other forest types

Lewis (1998)	Northwestern California	Federal	Evaluated the impacts of logging on erosion and suspended sediment transport in the Casper Creek watershed; South Fork harvested before 1990 FPRs; North Fork harvested after 1990 FPRs; measured and estimated suspended sediment concentrations.	Sediment load for the South Fork after road construction was 1475 kg ha ⁻¹ yr ⁻¹ and 2877 kg ha ⁻¹ yr ⁻¹ after harvesting; no effect in the North Fork watershed for sediment loads
Rice (1999)	Northwestern California	Private	Evaluated erosion from logging roads on the Redwood Creek watershed; measured erosion on 100 logging roads in the middle of the watershed.	Found the estimated erosion rate to be 177 m ³ km ⁻¹ ; noted that FPRs helped reduce erosion on logging roads
Jackson et al. (2001)	Coast Range (Washington)	Academia	Impacts of harvesting timber on 15 headwater streams; treatments included: (1) no harvest, (2) clearcut with un-thinned buffer, (3) clearcut with partial buffer, and (4) clearcut with buffer consisting of non-merchantable trees, and (5) clearcut with no buffer	Found that particle size distribution and habitat distributions were not different when compared to the no harvest treatments.
Rice et al. (2004)	Northwestern California	Non-profit	Forest management effects on erosion, sediment, and runoff; Casper Creek Experimental Watershed	Prior to the 1973 FPA, suspended sediment loads increased almost three-fold from road construction and selective logging; under the 1990 FPRs, there was a smaller, but significant increase in sediment from roads and clearcutting
Rashin et al. (2006)	Coast Range (Washington)	Non-profit	Effectiveness of timber harvest practices for controlling sediment related water quality impacts; used a weight-of-evidence approach to determine BMP effectiveness and was based on sediment delivery to streams, disturbance to stream channels, and aquatic	Stream buffers were effective at limiting chronic sediment delivery and disturbance to stream channels; stream buffers of at least 10 m were most effective for timber felling and yarding activities; factors influencing

			habitat conditions	BMP effectiveness included: proximity of ground disturbance near waterways, use of stream buffers, use of proper timber falling and yarding practices, minimizing stream channel disturbance, and timing of timber harvest
Jackson et al. (2007)	Washington	Academia	Abiotic and biotic response to 15 headwater streams from timber harvesting; treatments were same as Jackson et al. (2001)	No macroinvertebrate groups declined significantly over a three year period following the harvests; clearcutting with no SMZs had short-lived effects on some amphibian recovery
Karwan et al. (2007)	Northern Idaho	Academia	Effects of timber harvesting on suspended sediment loads in the Mica Creek Experimental Watershed; monitored seven automated stream monitoring flumes; pretreatment samples (1991-1997), post road construction samples (1998-2001), and post timber harvest samples (2001-2004); paired watershed approach (clearcut, partial harvest, reference)	Road construction did not significantly affect sediment loads; harvesting timber did have a significant and immediate impact on sediment loads for the clearcut watershed; no significant differences in partial harvest; after one year there were no significant differences between the clearcut and control watersheds
O'Conner et al. (2007)	Northwestern California	Federal	Evaluated sediment yield from first order streams from recent harvests and legacy practices; treatments included: (1) clearcut with a HCP, (2) clearcut without a HCP, and (3) control (un-harvested); captured transported sediment in sediment basins	Authors did not report any significant differences between sites that used a HCP and sites that did not; However, sites with a HCP tended to have lower sedimentation levels

Beschta and Jackson (2008)	Coast Range (Oregon)	Academia	Summarized sediment production from forest roads, logging, and slash burning on the Alsea Watershed	Management practices such as minimizing road construction, small clearcuts, buffer strips, and low severity burns help reduce sediment problems
Keppeler et al. (2008)	Northwestern California	Federal	Long-term patterns of hydrologic response after logging in a coastal redwood forest; Casper Creek Experimental Watershed	Post-treatments, sediment loads recovered quickly; however between 10-20 years after logging, sediment loads increased due to road failures on South Fork Watershed or due to pre-commercial thinning modifying hydrologic conditions on North Fork Watershed
Stednick (2008a)	Coast Range (Oregon)	Academia	Long-term streamflow changes following timber harvesting on the Alsea Watershed study sites	Annual water yield increases were not detectable on the Needle Branch watershed after 31 years; peak flow and low flow metrics were not significant from pretreatment measurements; Deer Creek had timber harvests since the original treatments and there were no significant flow metrics from pretreatment measurements; application of BMPs resulted in no significant differences
Stednick (2008b)	Coast Range (Oregon)	Academia	Long-term changes in water quality following timber harvesting on the Alsea Watershed study sites	Multiple timber harvests on Deer Creek did not have any significant changes in water quality (BMPs followed); Needle Branch (no buffer strips) had a significant increase in

				nitrate-nitrogen fluxes immediately after the treatment, but showed a quick return to pretreatment conditions
Gravelle et al. (2009)	Northern Idaho	Academia	Effects of timber harvesting on aquatic macroinvertebrate communities; sampling from 1994-2005 on Mica Creek Experimental Watershed; treatments: four year calibration period, four years of monitoring after forest roads were installed, and four years monitoring after timber harvest	Macroinvertebrate communities were not affected by road construction and timber harvesting; concluded that if BMPs are used appropriately, that similar areas to this study should have minimal effects on water quality and macroinvertebrate communities
Litschert and MacDonald (2009)	Sierra Nevada and Cascade mountains (California)	Academia	Assessed the frequency and characteristics of sediment delivery pathways on harvested sites on National Forest land; evaluated 200 harvested sites that included SMZs; used 'features' to describe eroded areas of the harvest	Found 19 features on the 200 sites caused by rills or gullies (15) and sediment plumes (4); 16 of the features started from skid trails; five skid trail features connected to streams; feature length was significantly related to hillslope gradient, mean annual precipitation, and elevation; sediment delivery to streams can be reduced by: (1) locating skid trails away from streams, (2) using waterbars with high surface roughness, and (3) closing skid trails.
Reiter et al. (2009)	Cascade Mountains (Washington)	Industry	Temporal and spatial turbidity patterns over 30 years in a managed forest; assessed sediment control methods and trends in turbidity	Turbidity had a declining trend even with active forest management; concluded that this was due to improvements to road construction and maintenance practices for

				reducing road sedimentation and runoff
Dubé et al (2010)	Washington	State	Washington road sub-basin scale effectiveness monitoring program; evaluated new FPRs for forest roads for improving protection of runoff and sediment delivery and determined how many roads meet the FFR performance targets; sampled 60-4 mile units	Found FFR targets for hydrology performance were met in 62% of the units and FFR targets for sediment protection were met in 88% of the units.
Elliot (2010)	Western United States	Federal	Effects of forest biomass used on watershed processes	Two general guidelines to reduce or minimize impacts on the watershed from biomass harvesting: (1) minimize disturbance to duff layer and (2) minimize number of roads and maintain roads; concluded that increased traffic on forest roads and compacting and disturbing the soil can affect runoff and erosion and that BMPs should be used to reduce any risks
Klein et al. (2012)	Northern California	Federal	Turbidity during winter runoff seasons after logging in 28 coastal watersheds	Rate of timber harvesting and watershed drainage areas can affect water quality; stated that hillslope hydrologic changes due to tree removal and root strength from decay should be included in the current BMPs and that erosion susceptible areas should limit rate of timber harvesting

Madej et al. (2012)	Northwestern California	Federal	Assessed changes in land use practices on sediment loads in the Panther Creek basin; treatment consisted of clearcut, thinning, and selective harvest and compared results to a control (un-harvested); evaluated sediment loads from timber harvesting methods and road designs	Found that sediment yields were higher on treatment site, however suspended sediments concentrations have decreased compared to previous periods due to improved management practices
Sugden et al. (2012)	Montana	State	Assessed Montana's forestry BMP program for the past 20 years; used past BMP audits	Forestry BMP implementation in 1990 was 78% and 97% in 2010; Water quality infractions per harvest site have decreased to <1 over the 20 years
Cafferata and Reid (2013)	Northwestern California	State	50 years of watershed research in the Casper Creek watershed; review of the past watershed experiments on the North Fork and South Fork watersheds	Author addressed key findings from past research; stated that research methods (monitoring technology and turbidity monitoring) conducted on the Casper Creek watershed have been used throughout the world; research is continuing on the watershed
USFS (2013)	Pacific Southwest Region (California)	Federal	Evaluated Pacific Southwest Region BMP program from 2008 to 2010; determine BMP implementation and effectiveness; 2237 randomly selected sites	BMP implementation was 91%; BMP effectiveness was 80%; BMPs for roads, range management, recreation, and mining were not as effective; noted effectiveness can be increased by improving erosion control plans and wet-weather standards.
Brandow and Cafferata	California	State	Evaluated California's FPRs implementation and effectiveness from 2008 to 2013; Coast,	Implementation of FPRs were high and effective in preventing

(2014)

Cascade, and Sierra Regions

sedimentation; 90% or higher implementation for watercourses and lake protection zones, roads, and crossings; suggested improvements for stream crossing design, construction and maintenance, and closure

Ziesak (2015) Montana

State

Montana's BMPs in regard to limiting non-point source pollution from forest operations; evaluated 42 sites for BMP effectiveness (2014 review)

42 sites evaluated for application and effectiveness; BMPs were applied 97% of the time; BMP were effective 98% of the time in protecting water quality; most frequent impacts on BMP effectiveness were associated with forest road maintenance and road surface drainage

2.7 Conclusion

Results from this literature review indicate that forestry BMPs minimize water quality effects of forest operations when implemented as recommended by state forestry agencies. While BMP effectiveness studies are often site or region specific, they clearly demonstrate a common outcome. Stuart and Edwards (2006) emphasized that BMPs based on physical principles continue to be effective with the passage of time. These effectiveness studies provide critical information and insight on how state BMP programs comply with the goals of the CWA. Forestry BMP effectiveness studies can help states formulate or update BMP guidelines.

Effectiveness research commonly notes that areas such as forest roads, skid trails, and stream crossings should receive considerable attention since they have the greatest potential for erosion and sediment delivery. Research studies from multiple regions across the U.S. have demonstrated that BMPs are effective and reduce sediment delivery to streams. Key conclusions on BMP effectiveness for the research studies examined here were divided into two categories: overall BMP effectiveness study conclusions and specific BMP guideline conclusions:

2.7.1 Overall BMP effectiveness study conclusions

- BMPs can minimize erosion and sedimentation.
- Implementation rates and quality are critical to BMP effectiveness for reduction of erosion and sediment yield.
- BMP implementation can be enhanced with pre-operation planning and with the involvement of a registered professional forester.
- Increased logger training and landowner knowledge of forestry BMPs can help improve implementation.

- Stream macroinvertebrates are typically not significantly affected by forest operations when BMPs are correctly applied.

2.7.2 Specific BMP guideline conclusions

- Forested SMZs are effective in trapping sediment and reducing stream TSS concentrations.
- Critically important BMP practices for forest roads include proper drainage structures, surfacing, erosion control of cut and fill slopes, traffic control, and closure.
- Sediment control structures applied to stream crossing approaches can significantly reduce runoff and sediment delivery.
- BMPs need to be applied during forest operations, not only as a closure measure.
- Effective skid trail closure practices can include installing waterbars and/or applying slash, mulch, or a combination of mulching and seeding.
- Improved stream crossings such as portable skidder bridges and temporary culverts can decrease TSS concentrations and turbidity compared to unimproved stream crossing structures.

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3.0 NATIONAL STATUS OF STATE DEVELOPED AND IMPLEMENTED FORESTRY BEST MANAGEMENT PRACTICES IN THE UNITED STATES

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3.1 Abstract

There have been few studies that compare monitoring strategies and implementation of forestry BMPs on a national level. This study surveyed state forestry agencies in each U.S. state. Survey responses were received from all 50 states. Each state has a documented BMP manual. Twenty states reported non-regulatory BMP guidelines, 19 reported quasi-regulatory BMP guidelines, and 11 reported regulatory BMP guidelines. Thirty-nine states have BMP monitoring programs with the state forestry agency as the lead agency in 35 states. Thirty-two states reported that they have conducted BMP implementation studies resulting in a mean national BMP implementation rate of 91%. However, when evaluating implementation of individual BMP categories, the survey indicated deficiencies for some states, yet these states' overall BMP implementation rate appear to be satisfactory. This assessment of state BMP programs indicates that BMP programs appear to be implemented at relatively high levels across the US.

3.2 Introduction

Forestry best management practice (BMP) guidelines were developed by U.S. states in response to the Federal Water Pollution Control Act of 1972, or Clean Water Act (CWA). CWA legislation as implemented by the US Environmental Protection Agency (EPA) required states to establish nonpoint source pollution (NPSP) control programs to meet water quality goals for forestry operations (Ice et al. 2004). In 1977, the EPA required states to develop either regulatory

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or non-regulatory forestry BMP programs (Ice et al. 2004) and in the 1987 reauthorization of the CWA, section 319 required the EPA and states to report to the U.S. Congress on the status of NPSP, impacts on water quality, and to create a plan for addressing any issues (Novotny 2003; US EPA 2005). By 2000, all 50 states had developed forestry BMP programs (Archev 2004; Shepard, 2006).

Since the CWA of 1972, forestry BMPs have evolved due to redefinitions of water quality standards with the majority of states revising BMP guidelines accordingly (Edwards and Stuart 2002; Archev 2004; Rummer 2004). State forestry agencies are commonly the lead agency in BMP guideline development (Edwards and Stuart 2002) and guidelines are often drafted by planning committees consisting of multiple disciplines (Helms 1998; Ice et al. 2004). Forestry BMP guidelines are associated with different operational activities and designed to control NPSP and may differ between states and regions.

State BMP guidelines include multiple forest operations categories such as timber harvesting, forest road construction and maintenance, log landings, skid trails, streamside management zones (SMZ's), stream crossings, wetland protection and management, site preparation, reforestation, and other categories depending on the state (Shepard 2006). In some states, additional BMP guidelines for wildlife protection (FDACS 2014) and woody biomass harvesting currently are in development (Fritts et al. 2014). Most Southeastern states have non-regulatory programs, although some states are quasi-regulatory, which occurs when BMPs are non-regulatory yet water quality infractions result in citations (Aust and Blinn 2004; SGSF 2007). Somewhat differently, Northeastern and Pacific Northwest states tend to enforce water quality infractions through Forest Practice Act laws.

States may conduct BMP implementation monitoring, compliance monitoring, or audits. Monitoring varies by state (Phillips and Blinn 2004) but procedures typically use a systematic process of identifying and evaluating the application of BMPs associated with forest operations (Ellefson et al. 2001). The term “compliance” has been used in the past when evaluating forestry BMPs; however, states now more commonly use the word “implementation”. Archey (2004) stated that terms like “implementation” and “compliance” are interpreted differently depending on state definitions. Regulatory states tend to use “compliance” while non-regulatory and quasi-regulatory states tend to use “implementation”.

The Southern Group of State Foresters (SGSFs) appointed a water resources task force to develop a regionally consistent approach for monitoring BMP implementation (SGSF 2007; Ice et al. 2010). The northeastern United States uses an implementation protocol developed by the U.S Forest Service’s Northeastern Area State and Private Forestry unit and the Northeastern Area Association of State Foresters Water Resources Committee (Welsch et al. 2006). These approaches and protocols for BMP implementation allow for standardized assessment and comparison across states in the region.

Few studies have evaluated the status and implementation of forestry BMPs on a national level. Most that have been conducted focused on individual states or regions. The SGSFs publishes a report periodically on implementation of forestry BMPs for the 13 southeastern states with the most recent report conducted in 2012 (SGSF 2012). The SGSFs implementation plan or “water goal” is that they want to “provide leadership and support to state agency programs that work to manage, conserve, restore, and enhance forests to provide a sustainable supply of clean water...” (SGSF 2008). The overall average BMP implementation for the 13 states in the 2012

report was 92% which was higher than the 87% rate reported in the 2008 study (SGSF 2008; SGSF 2012).

Ice et al. (2010) evaluated the trends of forestry BMPs in the United States. The authors used BMP implementation data reported by states and annual timber removal volumes for each state to develop a weighted national average implementation rate. The authors reported a national BMP implementation rate of 89%. Phillips and Blinn (2004) assessed BMP compliance monitoring approaches in the eastern United States. The authors found that northern states tend to focus monitoring on timber harvesting and forest roads while southern states focus on many more aspects of forest operations. Ice et al. (2004) conducted a review of BMP implementation and effectiveness of Forest Practice Rules and BMPs in the western United States. The authors found that monitoring methods in the West are now more statistically valid and consistent than past methods and that the BMP implementation rate for the region was 94%. The Council of Western State Foresters (CWSF) also conducted a review of BMPs in the western United States (CWSF 2007). Their objective was to summarize BMP implementation and effectiveness monitoring for each state they represent and results indicated BMP implementation ranged from 75% to 97% (8 states).

The National Association of State Foresters (NASF) began conducting surveys of state NPSP control programs for silviculture in 1992 (Edwards and Stuart 2002). Since then, the NASF has conducted additional surveys in 1994, 1996, 2000, and 2004 (Edwards and Stuart 2002; Archey 2004). The surveys measured the following forestry BMP variables: implementation rates, monitoring, policies, agencies involved, legislation, state regulation, effectiveness studies, and future needs (Archey 2004). Forty-eight states and 2 U.S. territories participated in the 2004 survey. Twenty-seven states reported BMP implementation data and the

mean national implementation rate was determined to be 91% which represented a 5% increase from 2000.

There are few studies assessing the status of state forestry BMPs on a national level. The past studies have found high rates of implementation, however most of these studies are dated and an updated assessment would be valuable to determine the current status of state forestry BMP in the United States. The objective of this project was to survey state forestry agency water quality (BMP) programs in the United States so that an updated assessment of state developed and implemented forestry BMPs can be conducted.

3.3 Methods

3.3.1 BMP survey

This project surveyed all 50 states regarding status and implementation of forestry BMPs. The initial survey was developed in March 2012 through the combined efforts of personnel at Virginia Tech and the NASF and was modeled on a previous BMP survey conducted by the NASF in 2004 (Archey 2004). In February 2013, the survey was finalized and converted to an online format. Survey questions involved a variety of BMP topics and some of the topics included BMP manuals, guidelines, regulation, monitoring, implementation, effectiveness, legislation, policies, and agencies and organizations involvement.

The Virginia Tech Institutional Review Board (VT IRB) reviewed and approved the survey along with pre-notice and follow-up e-mails in March 2013. Pre-notice letters were sent to the state forester in each state. In the pre-notice letter, the state forester was asked to forward the survey link to the appropriate forest water quality personnel in their state. The survey link was then sent to the state forester shortly after notification.

The survey was closed in December 2013 and responses were downloaded using Microsoft Excel. Both Microsoft Access and Microsoft Excel were used in formatting the survey results. ESRI ArcMap 10.2.2 was used to display survey results by state.

3.3.2 Statistical analysis

BMP implementation rates were analyzed to determine if implementation rates differed significantly by state BMP regulation and U.S. region. The dataset was formed from the BMP survey results and included the overall average state implementation rates and rates for 16 individual BMP implementation categories. Only 7 of 16 categories (timber harvesting, forest roads, skid trails, log landings, stream crossings, streamside management zones, and wetlands) were used in the analysis due to insufficient samples among the remaining 9 categories. Depending on data normality as verified by the Shapiro-Wilk test, data were either analyzed using standard one-way ANOVA or non-parametric Wilcoxon test (Zar 2010). Mean state implementation rates and skid trails were analyzed using parametric methods while timber harvesting, forest roads, log landings, stream crossings, streamside management zones, and wetlands were analyzed using non-parametric methods. Statistical analyses were conducted using JMP with an alpha level of 0.1 (SAS Institute Inc 2013).

3.4 Results

3.4.1 BMP manual and guidelines

The survey was completed by respondents from all 50 states. All respondents indicated their state has published a BMP manual (Table 4). However, BMP manuals for states such as Vermont (1987), Montana (1990), Oklahoma (1991), New Jersey (1995), Iowa (1996), Utah (1998), and Massachusetts (1999) were more than 15 years old. For example, Vermont's BMP manual was 27 years old. Forestry BMP manuals and BMP guidelines are available

electronically for 48 states (Table 4). The two states that did not report having online access to BMP manuals and guidelines listed an email address or mailing address to obtain BMP information for their state. Within the last five years, 25 states have written new BMP guidelines or have revised older BMP guidelines. Thirty-nine states have written new guidelines or revised them within the past 10 years.

Table 4. Most recent published state BMP manual, availability of online BMP manuals, and the agency(s) involved in writing or revising BMP guidelines for each state.

State	BMP manual year	Online access	Agency(s) involved	State	BMP manual year	Online access	Agency(s) involved	State	BMP manual year	Online access	Agency(s) involved
AL	2007	Yes	F	LA	2000	Yes	F, E	OH	2008	Yes	F, E, O
AK	2009	Yes	F, E, O	ME	2004	Yes	F, E, O	OK	1991	Yes	F, E, O
AZ	2013	No	F, O	MD	2005	Yes	F, E, O	OR	2010	Yes	F, O
AR	2002	Yes	*	MA	1999	Yes	F, E, O	PA	2001	Yes	F, E
CA	2013	Yes	F, E, O	MI	2009	Yes	F, E, O	RI	2003	No	F, E, O
CO	2010	Yes	F	MN	2013	Yes	F, O	SC	2012	Yes	F, E
CT	2012	Yes	F, E	MS	2008	Yes	*	SD	2003	Yes	F
DE	2006	Yes	F, E, O	MO	2006	Yes	F	TN	2003	Yes	F
FL	2008	Yes	F	MT	1990	Yes	F	TX	2010	Yes	F, E, O
GA	2009	Yes	F, E, O	NE	2001	Yes	*	UT	1998	Yes	F
HI	2007	Yes	*	NV	2008	Yes	F, E, O	VT	1987	Yes	F, E, O
ID	2013	Yes	F	NH	2005	Yes	F, E, O	VA	2011	Yes	F, E
IL	2007	Yes	F, E, O	NJ	1995	Yes	F, E, O	WA	2013	Yes	F
IN	2005	Yes	F, E, O	NM	2008	Yes	F, E, O	WV	2009	Yes	F, E, O
IA	1996	Yes	F	NY	2011	Yes	F, E	WI	2010	Yes	F, E
KS	2013	Yes	F, O	NC	2006	Yes	F	WY	2006	Yes	F, E
KY	2008	Yes	E, O	ND	2010	Yes	F, E, O				

*, No data reported; F, Forestry; E, Environmental; O, Other

3.4.2 BMP policy development

State forestry agencies were involved with BMP guideline and policy development in 45 states (Table 4 and 5). Four states reported no involvement with BMP policy development. Kentucky was the only state where the forestry agency was not involved with either guideline or policy development. Multiple agencies were involved in the development of BMP guidelines and policy in 34 states. Results indicated a range of environmental and other agencies are often involved in policy development for areas that deal with water resources (stream crossings, SMZs, and Wetlands) and chemical applications (chemical site preparation, pesticide applications, and fertilizer applications) (Table 5). Those commonly involved include the EPA, Department of Environmental Quality, U.S. Army Corps of Engineers, Department of Agriculture, Natural Resources Conservation Service, Department of Environmental Conservation, state water quality departments and divisions, forestry associations, university extension, fish and wildlife agencies, and others.

Table 5. Agencies involved in BMP policy development by forest operations category. Numbers reported in each column are the number of states that indicated that agency was involved. States may involve more than one agency.

Forest operations	Forestry	Environmental	Other
Timber harvest	41	5	4
Forest roads	43	8	4
Skid trails	44	6	4
Log landings	44	6	4
Stream crossings	40	16	7
SMZs	42	12	6
Wetlands	34	21	7
Reforestation	39	5	4
Mechanical site prep	36	5	5
Chemical site prep	26	13	13
Pesticide	25	21	13
Fertilizer	22	16	12
Prescribed burning	39	3	6
Wildfire suppression	35	2	4
Wildfire rehabilitation	33	4	3
Public lands	31	5	13

3.4.3 State forestry BMP regulation

BMP guidelines vary by state and region (non-regulatory, quasi-regulatory, or regulatory). Results indicated that 20 states have non-regulatory guidelines (11 in 2004), 19 quasi-regulatory guidelines (23 in 2004), and 11 regulatory guidelines (8 in 2004) (Figure 4). The 13 southeastern states that are part of the SGSFs primarily consist of non-regulatory and quasi-regulatory BMP guidelines, with Kentucky being the only southeastern state to report regulatory legislation. North Carolina uses quasi-regulatory guidelines but noted that their state has forest practice guideline legislation (North Carolina Sedimentation Pollution Control Act) for BMP application. The 20 states associated with the Northeastern Area Association of State Foresters (NAASF) primarily uses quasi-regulatory and regulatory BMP guidelines with only a few states using non-regulatory guidelines. Western states associated with the CWSFs (17 states)

primarily use regulatory and non-regulatory BMP guidelines with the Pacific Coast states consisting of regulatory guidelines as evidenced through state Forest Practice Acts. States also include legislation for different aspects of forest operations (timber harvesting, wetland protection, stream crossings, site preparation, site reforestation, and forest protection) with legislation in 14 states stemming from a state Forest Practice Act, 19 due to a state Anti-Sediment Law, 6 states related to a state Silvicultural Law, and 38 enacted in response to the Federal Water Pollution Control Act (Table 6).

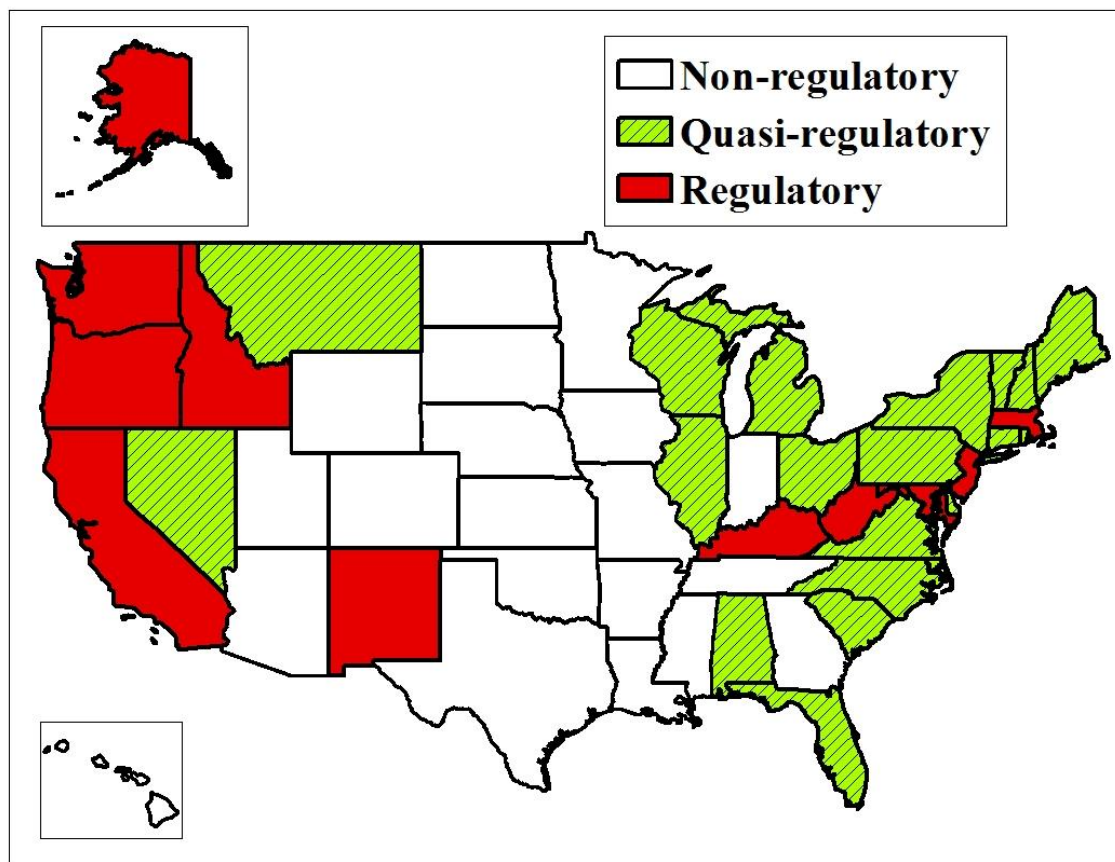


Figure 4. State forestry BMP guideline regulations. States consist of non-regulatory, quasi-regulatory, or regulatory BMP guidelines. Quasi-regulatory states have non-regulatory BMP guidelines, but water quality infractions may result in fines.

Table 6. Number of respondents that reported their state having BMP legislation for different forest operation categories. The table also includes the total number of states represented by each legislation.

State legislation	Timber harvesting	Wetland protection	Stream crossings	Site preparation	Site reforestation	Forest protection	Total number of states
Federal Water Pollution Act	27	35	33	18	10	8	35
State Forest Practices Act	13	11	12	11	11	12	14
State Anti-Sediment Law	16	13	18	12	9	7	19
State Silvicultural Law	6	5	5	4	5	5	6
State Non-Regulatory BMPs	37	30	33	29	28	29	38
Other	11	12	12	6	6	9	18

3.4.4 BMP monitoring

Thirty-nine states reported that they monitor BMPs, which is up from 29 states in 2004 (Table 7). Thirty-six states reported their most recent monitoring year with 34 states reporting that future monitoring is planned. State BMP monitoring cycles ranged from 1 to 11 years with 21 states (42%) monitoring BMPs between 1 and 3 years. The lead agency conducting BMP monitoring is the state forestry agency in 35 states (Table 7). Ohio and New York reported that an organization other than the state forestry agency is responsible for BMP monitoring and those organizations, respectively, are the Ohio Forestry Association and New York's Watershed Agricultural Council. Eight states reported that multiple state agencies are involved with BMP monitoring (EPA, Department of Agriculture, Department of Environmental Conservation, Department of Environmental Quality, Department of Agriculture, Department of Fish and Game, and others).

States also reported whether they monitor BMPs pre-harvest, during-harvest, or post-harvest (Table 7). Thirty-seven states reported monitoring after completion of a timber harvest with seventeen also monitoring implementation during multiple phases of a timber harvest. Nine states reported pre-harvest monitoring which most likely consists of pre-harvest planning. Eighteen states reported that they conduct monitoring during a timber harvest.

Table 7. Respondents that reported their state monitors forestry BMPs along with the next planned year of monitoring, the agency(s) involved in monitoring, and whether monitoring is conducted pre-harvest, during-harvest, or post-harvest.

State	Most recent year	Next planned year	Agencies involved	Time of monitoring	State	Most recent year	Next planned year	Agencies involved	Time of monitoring
AL	2012	2014	F	PR, D, PO	MT	2012	2014	F	D, PO
AK	2012	2013	F, O	PR, D, PO	NE	*	*	*	*
AZ	2013	2014	F	PO	NV	*	*	F, E	PR, D, PO
AR	2011	2015	F	PO	NH	*	*	*	*
CA	2012	2020	F, O	PR, D, PO	NJ	2013	2013	F	PR, D, PO
CO	2012	2014	F	PO	NM	*	*	*	*
CT	*	*	*	*	NY	2011	*	O	PO
DE	*	*	*	*	NC	2008	2014	F	D
FL	2011	2013	F	D, PO	ND	*	*	*	*
GA	2013	2013	F	D, PO	OH	2012	2013	O	D, PO
HI	*	*	*	*	OK	2010	2014	F	PO
ID	2012	2016	F, E	D, PO	OR	2002	2013	F	PO
IL	*	*	*	PR, D, PO	PA	*	*	*	PO
IN	2013	2014	F, O	PO	RI	2013	*	F	PR
IA	*	*	*	*	SC	2012	2015	F	PO
KS	*	*	*	*	SD	*	*	*	*
KY	2012	2013	F	D, PO	TN	2010	2015	F	PO
LA	2012	2015	F	PO	TX	2011	2014	F	PO
ME	2011	2014	F	D, PO	UT	2010	2015	F	PR, D, PO
MD	2005	2014	F, O, NGO	PO	VT	2012	2013	F, E, O	D, PO
MA	2013	2014	F, E	PR, D, PO	VA	2012	2013	F	PO
MI	2011	2014	F	D, PO	WA	2012	2013	F	PO
MN	2011	2014	F	PO	WV	2013	2014	F	PO
MS	2010	2014	F	PO	WI	2008	2013	F	PO
MO	2013	2014	F	PO	WY	*	*	*	*

*, No data reported; F, Forestry; E, Environmental; O, Other; NGO, Non-Government Organization; PR, Pre-Harvest; D, During-Harvest; PO, Post-Harvest

3.4.5 BMP implementation

Supplemental to BMP monitoring, many states have formal BMP implementation surveys, BMP audits, or BMP compliance surveys that include implementation rates. Thirty-two states reported BMP implementation rate data (Figure 5) compared to 27 states in the 2004 survey. Respondents reported implementation data for applicable forest operations in their state (16 categories) and a mean implementation rate for each state was then calculated. Mean state BMP implementation rates ranged from 80% to 99%. The mean BMP implementation for the U.S. in this study was 91% and calculated using the mean of each state implementation rate. The 2004 survey consisted of 27 states reporting a mean implementation rate of 91% (Archey 2004).

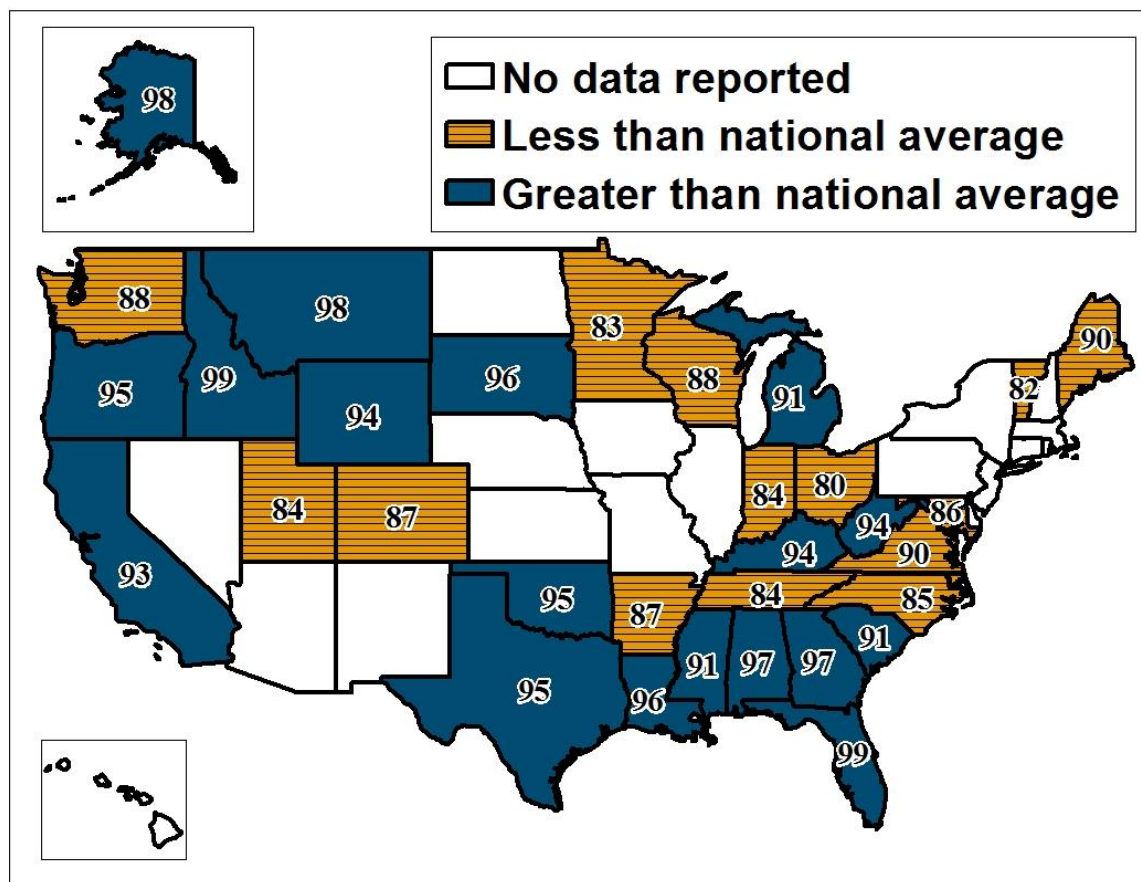


Figure 5. State forestry BMP implementation rate (%) for respondents that reported their state previously conducted implementation studies, BMP audits, or compliance studies. States in white did not have any data reported. The national average implementation rate is 91%.

State BMP implementation results were divided into state regulation categories (non-regulatory, quasi-regulatory, and regulatory) (Tables 8-10). Thirteen non-regulatory states reported mean state implementation rates ranging from 82.8% to 96.5% and the mean rate was 90.2% (Table 8). Georgia reported the highest implementation rate for non-regulatory states (96.5%) followed by Louisiana (96.0%), South Dakota (96.0%), Texas (95.4%), Oklahoma (94.6%), Wyoming (94.0%), Mississippi (90.5%), Arkansas (87.4%), Colorado (87.0%), Indiana (84.4%), Tennessee (84.2%), Utah (84.2%), and Minnesota (82.8%).

Table 8. BMP implementation rates (%) by forest operation category for states that respondents reported their state having non-regulatory BMP guidelines. The mean implementation rate for the 13 non-regulatory states is 90.2%.

Non-regulatory states	AR	CO	GA	IN	LA	MN	MS	OK	SD	TN	TX	UT	WY	
	Percent (%)													
Forest operations														Mean
Timber harvest	95	*	98	86	96	*	*	92	91	*	*	89	*	92.4
Forest roads	85	*	94	95	96	86	84	94	94	88	95	85	*	90.5
Skid trails	*	*	95	78	96	*	84	75	94	85	98	89	*	88.2
Log landings	*	*	99	91	96	90	94	96	100	92	99	87	*	94.4
Stream crossings	84	*	93	74	96	91	92	93	98	82	85	86	*	88.5
SMZs	86	*	95	82	96	71	94	96	90	88	90	70	*	87.1
Wetlands	*	*	97	82	96	87	95	100	*	70	98	51	*	86.2
Reforestation	95	*	100	*	96	*	*	97	*	*	96	87	*	95.2
Mechanical site prep	74	*	95	*	96	92	*	97	*	*	98	100	*	93.1
Chemical site prep	100	*	100	*	*	75	*	100	*	*	98	*	*	94.6
Pesticide	*	*	100	*	*	75	*	100	100	*	98	*	*	94.6
Fertilizer	*	*	100	*	*	*	*	*	*	*	*	*	*	100.0
Prescribed burning	80	*	84	*	*	78	*	93	100	*	94	76	*	86.4
Wildfire suppression	*	*	100	*	*	*	*	*	*	*	*	*	*	100.0
Wildfire rehabilitation	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Public lands	*	*	98	87	*	*	*	97	97	*	*	100	*	95.8
State mean	87.4	87.0	96.5	84.4	96.0	82.8	90.5	94.6	96.0	84.2	95.4	83.6	94.0	
Non-regulatory mean	90.2													

*, No data reported

Implementation rates for individual forest operation categories ranged from 86.2% to 100%. Forest operations categories that were below the mean implementation rate for non-regulatory BMPs included: skid trails (88.2%), stream crossings (88.5%), SMZs (87.1%), wetlands (86.2%), and prescribed burning (86.4%).

Eleven quasi-regulatory states reported implementation rates ranging from 80.3% to 99.4% with a mean of 90.2% (Table 9). Florida reported the highest implementation rate for quasi-regulatory states (99.4%) followed by Montana (98.2), Alabama (96.9%), Michigan (91.3%), South Carolina (91.1%), Maine (90.3%), Virginia (89.9%), Wisconsin (87.8%), North Carolina (84.6%), Vermont (82.2%), and Ohio (80.3%). Individual forest operation categories that were below the mean BMP implementation rate included: forest roads (89.4%), skid trails (88.0%), stream crossings (84.6%), and prescribed burning (89.0%).

Table 9. BMP implementation rates (%) by forest operation category for states that respondents reported their state having quasi-regulatory BMP guidelines. The mean implementation rate for the 11 quasi-regulatory states is 90.2%.

Quasi-regulatory states	AL	FL	ME	MI	MO	NC	OH	SC	VT	VA	WI	
	Percent (%)											
Forest operations												Mean
Timber harvest	98	99	90	*	99	*	85	94	*	*	97	94.6
Forest roads	93	99	89	91	97	84	83	98	94	85	70	89.4
Skid trails	*	100	89	87	99	82	73	*	84	90	88	88.0
Log landings	*	100	97	99	100	*	81	*	70	94	*	91.6
Stream crossings	96	98	81	86	94	72	78	81	68	92	*	84.6
SMZs	97	98	93	94	97	91	81	92	86	92	89	91.8
Wetlands	*	99	93	91	100	*	81	*	91	92	95	92.8
Reforestation	*	99	*	*	100	*	*	100	*	*	*	99.7
Mechanical site prep	98	99	*	*	*	*	*	93	*	74	*	91.0
Chemical site prep	98	100	*	*	*	*	*	93	*	100	*	97.8
Pesticide	*	100	*	*	*	*	*	100	*	*	*	100.0
Fertilizer	*	100	*	*	*	*	*	*	*	*	*	100.0
Prescribed burning	98	100	*	*	97	*	*	60	*	90	*	89.0
Wildfire suppression	*	100	*	*	*	*	*	*	*	*	*	100.0
Wildfire rehabilitation	*	100	*	*	*	*	*	*	*	*	*	100.0
Public lands	*	100	*	*	99	94	*	100	*	*	*	98.3
State mean	96.9	99.4	90.3	91.3	98.2	84.6	80.3	91.1	82.2	89.9	87.8	
Quasi-regulatory mean	90.2											

*, No data reported

State implementation rates for the eight regulatory states that reported data ranged from 86.4% to 98.5% with a mean implementation rate of 93.3% (Table 10). Idaho reported the highest mean state implementation rate (98.5%) followed by Alaska (97.6%), Oregon (95.3%), West Virginia (94.4%), Kentucky (93.7%), California (93.0%), Washington (87.5%), and Maryland (86.4%). Timber harvesting (91.5%), skid trails (92.7%), and stream crossings (86.9%) were lower than the mean state implementation rate.

Table 10. BMP implementation rates (%) by forest operation category for states that respondents reported their state having regulatory BMP guidelines. The mean implementation rate for the 8 regulatory states is 93.3%.

Regulatory states	AK	CA	ID	KY	MD	OR	WA	WV	
	Percent (%)								
Forest operations									Mean
Timber harvest	98	*	99	88	81	98	*	85	91.5
Forest roads	95	96	98.5	92	93	98	85	94	93.9
Skid trails	*	95	99	92	78	96	*	96	92.7
Log landings	99	93	99	92	98	99	85	98	95.4
Stream crossings	97	83	100	96	67	71	85	96	86.9
SMZs	99	98	90	96	82	96	*	96	93.9
Wetlands	*	*	100	100	93	88	95	96	95.3
Reforestation	*	*	*	*	*	100	*	*	100.0
Mechanical site prep	*	*	98	*	*	98	*	*	98.0
Chemical site prep	*	*	100	*	*	98	*	*	99.0
Pesticide	*	*	100	*	*	98	*	*	99.0
Fertilizer	*	*	100	*	*	98	*	*	99.0
Prescribed burning	*	*	*	*	*	100	*	*	100.0
Wildfire suppression	*	*	*	*	*	*	*	*	*
Wildfire rehabilitation	*	*	*	*	*	*	*	*	*
Public lands	*	*	99	*	99	96	*	*	98.0
State mean	97.6	93.0	98.5	93.7	86.4	95.3	87.5	94.4	
Regulatory mean	93.3								

*, No data reported

No significant differences ($p = 0.37$) were found between mean state BMP implementation rates for non-, quasi- and regulatory states (Table 11). However, there was a significant difference ($p < 0.1$) between state regulation and streamside management zone (SMZ) implementation rates ($p = 0.05$). SMZ implementation rates for regulatory (94.6%) and quasi-regulatory (91.8%) states were significantly higher than implementation rates of non-regulatory states (87.1%).

Table 11. BMP implementation rates evaluated by state regulation. Mean implementation rates (%) followed by different letters are significantly different at an alpha level <0.1. Tukey's HSD* and Wilcoxon† post hoc subgroups shown for the appropriate statistical test.

BMP implementation category	Regulation	N	Mean implementation rate (%)	P-values
Overall state*	Regulatory	8	93.4 a	0.3778
	Quasi-Regulatory	11	90.1 a	
	Non-Regulatory	13	90.2 a	
Timber harvest†	Regulatory	7	92.7 a	0.6628
	Quasi-Regulatory	7	94.6 a	
	Non-Regulatory	7	92.4 a	
Forest roads†	Regulatory	9	94.6 a	0.1839
	Quasi-Regulatory	11	89.4 a	
	Non-Regulatory	11	90.5 a	
Skid trails*	Regulatory	7	93.7 a	0.3126
	Quasi-Regulatory	9	88.0 a	
	Non-Regulatory	9	88.2 a	
Log landings†	Regulatory	9	95.9 a	0.7406
	Quasi-Regulatory	7	91.6 a	
	Non-Regulatory	10	94.4 a	
Stream crossings†	Regulatory	9	88.3 a	0.5223
	Quasi-Regulatory	10	84.6 a	
	Non-Regulatory	11	88.5 a	
Streamside Management Zone†	Regulatory	8	94.6 a	0.0594
	Quasi-Regulatory	11	91.8 ab	
	Non-Regulatory	11	87.1 b	
Wetlands†	Regulatory	6	95.3 a	0.5224
	Quasi-Regulatory	8	92.8 a	
	Non-Regulatory	9	86.2 a	

BMP implementation rates were also analyzed by region (northeast, southeast, and west) (Table 12). Mean state implementation rates were significantly higher ($p < 0.1$) for western (93.2%) and southeastern states (92.4%) than northeastern states (86.4%). Western and southeastern states implementation rates for timber harvesting (96.3% and 95%, respectively), stream crossings (90.4% and 89.2%, respectively), and SMZs (92.5% and 93.2%, respectively) were significantly higher ($p = 0.01$, $p = 0.05$, and $p = 0.03$, respectively) than northeastern states (87.3%, 80.1%, and 86.0%, respectively). Western states forest road (94.3%) and skid trail (90.1%) implementation rates were significantly higher ($p = 0.08$ and $p = 0.01$, respectively) than northeastern states (88.3% and 84.1%, respectively).

BMP implementation data were also compared to the past two surveys conducted by the NASF (Table 13). The 16 BMP categories used in this study could not fully be compared due to past surveys combining or not evaluating some of the forest operations categories. Mean BMP implementation was 86% (2000 and 2004) compared to 93% (2013) for comparable forest operation categories.

Table 12. BMP implementation rates evaluated by region. Mean implementation rates (%) followed by different letters are significantly different at an alpha level <0.1. Tukey's HSD* and Wilcoxon[†] post hoc subgroups shown for the appropriate statistical test.

BMP implementation category	Region	N	Mean implementation rate (%)	P-values
Overall state*	West	10	93.2 a	0.0098
	Southeast	13	92.4 a	
	Northeast	9	86.4 b	
Timber harvest [†]	West	7	96.3 a	0.0131
	Southeast	8	95.0 a	
	Northeast	6	87.3 b	
Forest roads [†]	West	9	94.3 a	0.0863
	Southeast	13	91.3 ab	
	Northeast	9	88.3 b	
Skid trails*	West	7	96.0 a	0.0116
	Southeast	10	89.7 ab	
	Northeast	8	84.1 b	
Log landings [†]	West	9	95.8 a	0.1954
	Southeast	9	95.8 a	
	Northeast	8	90.5 a	
Stream crossings [†]	West	9	90.4 a	0.0584
	Southeast	13	89.2 a	
	Northeast	8	80.1 b	
Streamside Management Zone [†]	West	8	92.5 a	0.0384
	Southeast	13	93.2 a	
	Northeast	9	86.0 b	
Wetlands [†]	Southeast	9	94.1 a	0.1089
	West	5	86.8 a	
	Northeast	9	89.9 a	

Table 13. BMP implementation results from the recent survey (2013) compared to the 2004 and 2000 survey results. The 2000 and 2004 surveys included a few different forest operation categories. Forest operation categories that were similar were used in this table for comparison. In the past, forest roads and skid trails, mechanical site preparation and chemical site preparation, and pesticide and fertilizer applications were combined (noted in table)

Forest operations	2013 implementation (states reporting)	2004 implementation (states reporting)	2000 implementation (states reporting)
	Percent (%)		
Forest roads	91 (30)		
Skid trails	89 (24)		
Forest roads and skid trails (combined)		89 (14)	83 (16)
Stream crossings	87 (29)	78 (13)	79 (13)
SMZs	91 (29)	85 (16)	80 (14)
Wetlands	91 (23)	83 (9)	88 (4)
Mechanical site prep	93 (13)		
Chemical site prep	97 (11)		
Site prep (combined)		87 (7)	95 (6)
Pesticide	97 (9)		
Fertilizer	99 (4)		
Chemical use (combined)		96 (6)	92 (6)
Mean	93	86	86

3.4.6 BMP effectiveness studies

Thirty-three respondents stated that their state had previously or were currently conducting BMP effectiveness studies (Table 14 and Figure 6), which is an increase of 10 states from the 2004 survey. Nineteen of the effectiveness studies were conducted between 2012 and 2013. Nineteen respondents also indicated their state had future effectiveness studies planned. Agencies involved in conducting the effectiveness studies included forestry agencies, academia, environmental organizations, non-government organizations, and other organizations.

Table 14. Respondents that responded ‘yes’ to their state conducting BMP effectiveness studies. If applicable, most recent year, current ongoing study, next planned study, and agency conducting the studies were reported.

State	Most recent	Next planned	Agency	State	Most recent	Next planned	Agency
AL	2012	*	*	NJ	2013	2013	F
AK	2012	2014	F, O	NC	2012	2013	F
AZ	2013	2014	F	OH	2012	2013	O
AR	2006	*	A	OK	2012	*	A
CA	2008	2013	F	OR	2013	*	F
DE	2002	*	F	PA	*	*	*
FL	2013	2013	F,A	SC	*	*	*
GA	2012	*	A, NGO	SD	2009	2014	O
IN	2012	2013	F, O	TX	2007	2015	F
KY	2013	*	A,O	UT	2010	2015	F
ME	2011	2013	F	VT	*	*	F
MD	2005	2014	F	VA	2012	*	F, A
MI	*	*	E	WA	2012	2013	O
MN	2008	*	A,O	WV	2013	2014	F
MS	2013	2014	F	WI	2012	*	F
MO	2013	2014	F	WY	2011	2013	F
MT	2012	2014	F				

*, No data reported; A, Academia; F, Forestry; E, Environmental; O, Other; NGO, Non-Government Organization

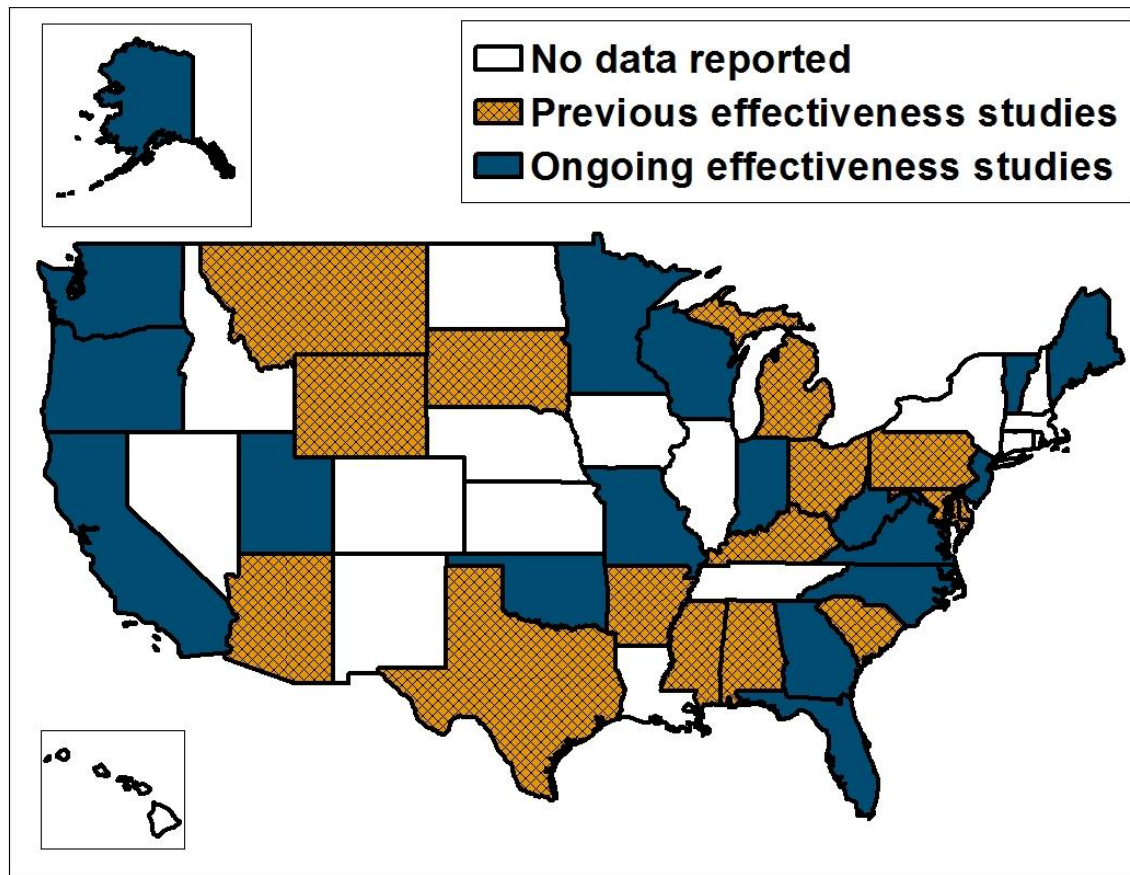


Figure 6. Survey responses for states that have conducted BMP effectiveness studies in the past and states that currently have ongoing effectiveness studies.

3.4.7 Estimated cost to implement BMPs

Respondents estimated costs to implement BMPs (minor, medium, or high) in their state for the forestry agency, landowners, and loggers (Figure 7). The costs estimates were associated with each of the state's applicable forest operations categories and then averaged to determine a mean estimated cost. The majority of implementation costs were associated with being minor or medium (forestry agency, 20 states and 21 states, respectively; landowners, 24 states and 19 states, respectively; loggers, 15 states and 27 states, respectively). Few respondents indicated costs to implement BMPs were high for their forestry agency, landowners, and loggers (4 states, 1 state, and 2 states respectively).

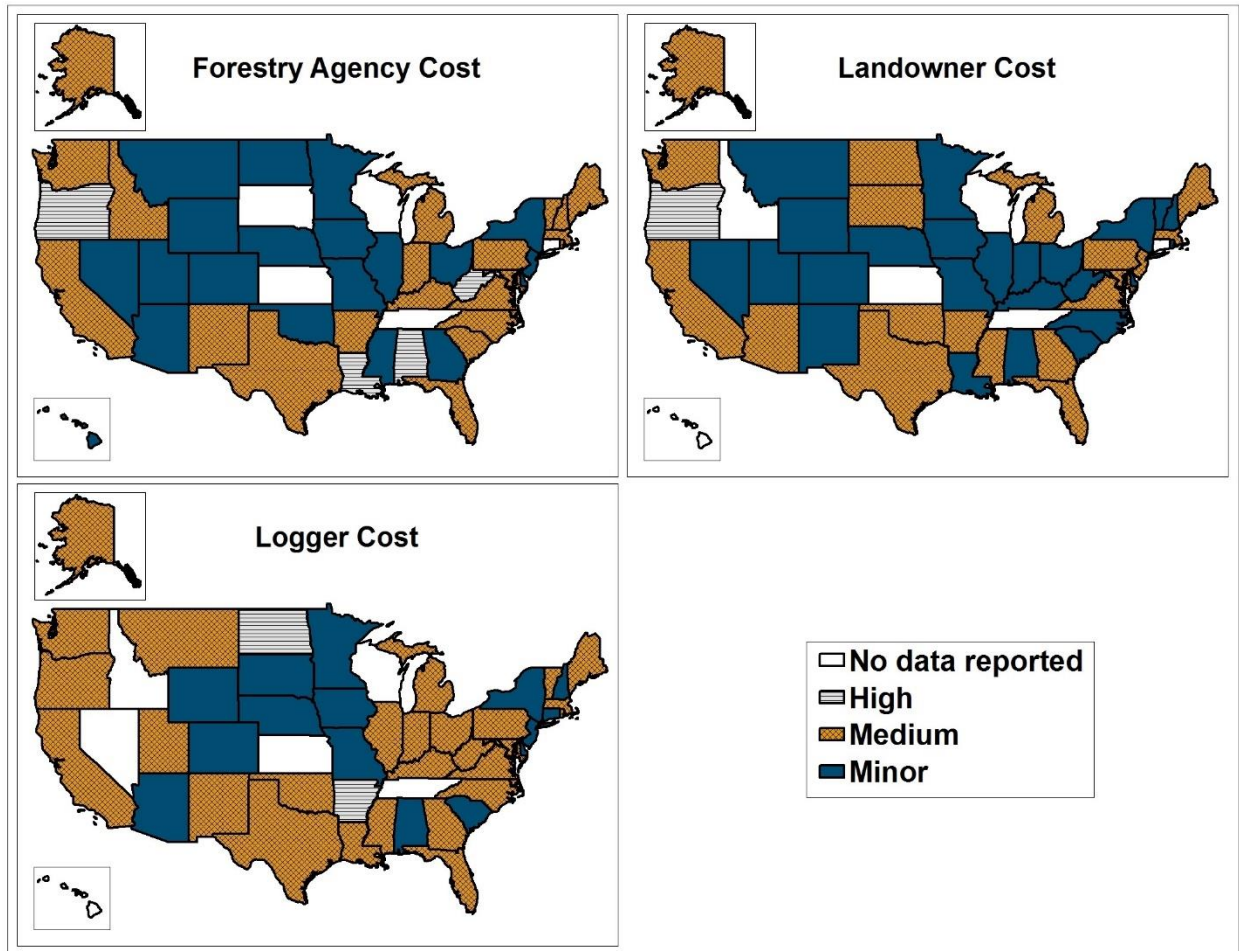


Figure 7. Average cost to implement BMPs by state as reported by the respondents. Respondents had three options to choose from: minor, medium, or high for each of the 16 applicable forest operation categories and the average response was then calculated.

3.4.8 Rating of state BMP program

Respondents were asked to rate their state forestry BMP program (not applicable, not effective, somewhat effective, effective, and highly effective) for each applicable forest operations category (Figure 8). Forty-eight respondents reported ratings which were averaged to determine a mean state rating. No state programs received a not effective rating with two respondents rating their state BMPs as somewhat effective.

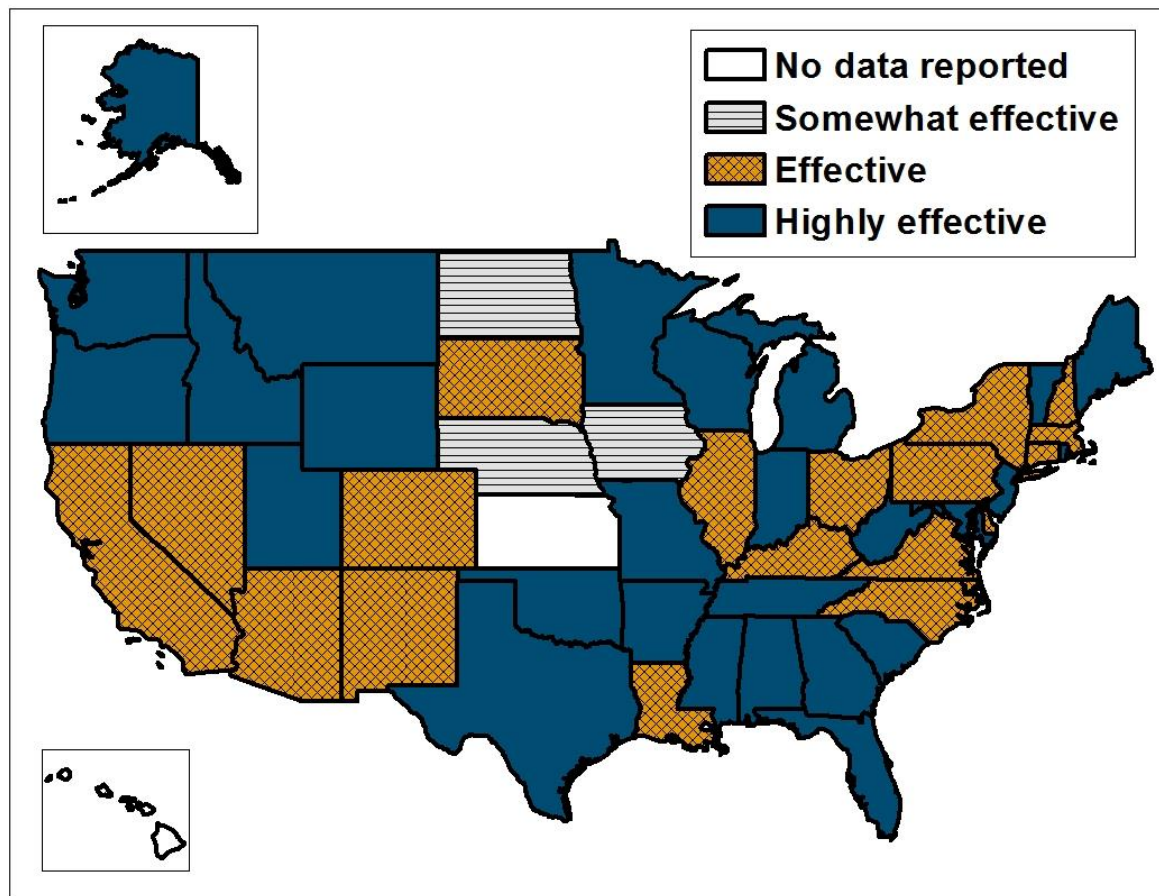


Figure 8. Average rating of state BMP programs as reported by respondents. Respondents rated all applicable forest operation categories (not effective, somewhat effective, effective, or highly effective) and a mean score was calculated for each state. None of the mean scores were rated as not effective.

3.4.9 Employees allocated to state water quality program

Forty-four respondents reported data on employees allocated to their state water quality program (Table 15). States reported number of employees in full time equivalent (FTE) metrics, which are the number of full-time employees (1 FTE = 1 full-time employee). FTEs ranged from 0 to 101.3. The majority (33) of the states have 0 to 6.5 FTEs allocated to their state water quality program for actual water quality personnel. States with high FTEs associated their on-the-ground foresters and law enforcement personnel (regulatory states) with their water quality program.

Table 15. Respondents that reported their state Full Time Equivalent (FTE) associated with their states forest water quality (1 FTE = 1 full time employee).

State	FTE	State	FTE	State	FTE	State	FTE	State	FTE
AL	1	HI	*	MA	*	NM	10	SD	0
AK	6.5	ID	18.5	MI	*	NY	0	TN	10
AZ	0.1	IL	5	MN	1.1	NC	13.5	TX	4.4
AR	1	IN	1.5	MS	1	ND	1	UT	0.5
CA	50	IA	0	MO	0.25	OH	0.21	VT	1.5
CO	4.5	KS	*	MT	13.5	OK	1.1	VA	67
CT	0.1	KY	20.5	NE	0.1	OR	39	WA	101.3
DE	5	LA	0	NV	0	PA	*	WV	31
FL	2.5	ME	3.5	NH	0.7	RI	1	WI	*
GA	6.2	MD	1.9	NJ	0	SC	4	WY	0

*, No data reported

3.5 Discussion

This study provided an updated assessment of state forestry BMP programs in the United States. Few studies have assessed BMPs on a national level, with most studies being dated and/or on a region level. However, results indicate that many states are very active with regard to BMPs with 32 states conducting implementation studies, compliance studies, or BMP audits. These states also often report their study results on agency websites which are accessible to the public.

States began developing and implementing forestry BMPs in an organized manner following passage of the Federal Water Pollution Act of 1972. Past research reports that BMPs have and will evolved over time due to changes in water quality standards (Archev 2004; Rummer 2004; Edwards and Stuart 2002) or use of new technology, thus it is essential that states maintain relevant BMP manuals. Seventy-eight percent of states have written new guidelines and revised old guidelines within the last 10 years which shows that BMPs are evolving over time. States have also mostly kept BMP manuals up-to-date with 22% of states using BMP manuals more than 10 years old.

State BMP regulation can be a controversial topic, particularly in states where forestry BMPs are considered voluntary (Edwards and Stuart 2002). States that have regulatory guidelines through a state Forest Practice Act usually enforce action for NPSP issues from forestry operations rather than enforcing action on whether forestry BMPs were applied. Quasi-regulatory BMPs are similar and usually have some type of enforcement for certain water quality standard violations and may be issued through the state forestry agency and/or another agency in the state that has regulatory action. This study found no significant difference between state regulation and mean state BMP implementation. From the survey results, the type of state regulation does not typically influence mean BMP implementation rates. However, it was found that SMZ guidelines have higher implementation for regulatory and quasi-regulatory states. These BMP implementation rates are used as surrogates for water quality protection which seems reasonable as properly applied BMPs have been found to minimize erosion and sedimentation which are the main sources of NPSP from forest operations (Cristan et al. 2016).

Mean state BMP implementation rates are high overall; however, some states reported deficiencies for individual BMP guidelines even though their overall state BMP implementation

rate was high. When assessing mean state implementation rates, these deficiencies are not noticeable. States evaluate multiple BMP guidelines and take an average of all the evaluated guidelines to formulate a mean state implementation rate which may not show any deficiencies, especially if only a small number of guidelines are deficient. Assessing mean implementation rates for states may not always be the best representation on how individual BMP guidelines are being implemented. Evaluating individual BMP guidelines in this study allowed for detection of possible deficiencies. As reported here, states do not have the same methods of conducting implementation studies, compliance studies, or BMP audits; however, they tend to be similar within regions of the United States. An interesting study would compare the way that states present their mean state implementation rate and the efficacy of a standard protocol.

The national BMP implementation rate for the 2000 survey was 86% with the northeastern region being lower than the national average of 82% (Edwards and Stuart 2002). BMP implementation rates from the 2013 survey were also found to be lower for the northeastern region (86%) when compared to the other regions (southeast 92% and west 93%) and national average (91%). Northeastern state BMP implementation rates were significantly lower than southeastern and western regions. Phillips and Blinn (2004) reported that northern states tend to evaluate BMPs on timber harvests and roads while southern states evaluate BMPs on a wide range of forest operations categories. Lower implementation rates can also be a result on how sites are monitored with the northeastern region having their own protocol for implementation monitoring.

The survey found some discrepancies in respondent replies. The main discrepancy was whether BMP effectiveness studies have been conducted. Cristan et al. (2016) recently conducted a review of past BMP effectiveness studies in the United States and found that a few

respondents were apparently not aware of existing studies in their state. This may be a result of the respondent not having knowledge of other agencies, organizations, or academic research studies on BMP effectiveness. Future surveys may need to be sent to multiple agencies, organizations, or academic institutions within each state to obtain proper evaluation of state BMPs. Only a few states reported that they involved multiple personnel or agencies in survey responses. These results may also indicate that BMP research needs to be more effectively transmitted to practitioners. The survey asked respondents what improvements could be made to their state BMP program that would enhance it. The majority of the responses included:

- Funding for a sustained BMP program (for states that do not monitor BMPs);
- Increase employees allocated to water quality/BMP programs;
- Funding for outreach, education, and logger training;
- Cost-share programs for loggers and landowners to lower costs of BMP implementation;
- and
- Update current BMP guidelines.

Overall implementation rates of states are generally greater than 90% which is similar to past surveys; however, there are potential deficiencies when evaluating individual BMPs. This survey allowed for an updated assessment of state BMP programs in the United States. The main findings of the survey include:

- Fifty states reported having BMP guidelines/manuals with 48 states reporting online access to guidelines/manual;
- The national BMP implementation rate is 91% (32 states), similar to the 2004 results (27 states);

- No significant differences between state regulation and mean state BMP implementation rates were detected;
- Regulatory and quasi-regulatory SMZ guideline implementation rates were significantly higher than non-regulatory guidelines;
- The western and southeastern regions implementation rates were significantly higher than the northeastern region;
- Significant differences were found for skid trails, timber harvesting, SMZs, stream crossings, and forest roads when evaluated by the three regions;
- Past BMP effectiveness studies were reported for 33 states with 19 states reporting future effectiveness studies (23 states in 2004); and
- Within the last 5 years, 25 states have written new guidelines or revised old guidelines.

3.6 Acknowledgements

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4.0 A METHOD FOR PREDICTING POTENTIAL FOREST HARVESTING INDUCED EROSION RATES WITH DIFFERENT LEVELS OF BMPS

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4.1 Abstract

Forest erosion studies in the southeastern U.S. have quantified erosion from different aspects of a timber harvest (clearcut, forest road, skid trails, and stream crossings, etc.); however, few studies have quantified erosion from an overall timber harvest. This study used literature that is reflective of current timber harvesting (1999-present) to develop a literature derived database for timber harvests and subsequently developed a simple method (Virginia Tech Harvest Erosion Estimation Method (VTHEEM)) to estimate an erosion rate for timber harvests. VTHEEM is based on operation area and literature derived erosion rates. Literature from four southeastern physiographic regions (Mountains, Piedmont, Gulf Coastal Plain, and Atlantic Coastal Plain) were reviewed. Erosion rate studies were deemed insufficient in the Mountains (3), Gulf Coastal Plain (7), and Atlantic Coastal Plain (1) for inclusion in method development. However, the VTHEEM could be developed for the Piedmont region due to more recent studies within the region (13) that represented the operation categories of interest (timber harvesting, forest roads, skid trails, logging decks, streamside management zones, and stream crossings). The VTHEEM is not intended for research level prediction of erosion as research or regulatory tools, rather it was designed to allow forest managers to predict an overall timber harvest erosion rate and examine the most efficient use of best management practices (BMPs) to minimize potential

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water quality problems. Users can input the area and select a low, average, or high erosion rate based on previous studies for each appropriate operation category.

The literature-derived VTHEEM was compared to field based-soil erosion estimates (Universal Soil Loss Equation-Forest) collected on four Piedmont (Virginia) timber harvests. Average overall potential erosion for the four timber harvests was similar between the VTHEEM outputs and the USLE erosion rates ($0.6 \text{ ton ac}^{-1} \text{ yr}^{-1}$ and $0.7 \text{ ton ac}^{-1} \text{ yr}^{-1}$, respectively). Barrett et al. (2016) estimated average erosion from timber harvests in the Piedmont region to be $0.8 \text{ ton ac}^{-1} \text{ yr}^{-1}$.

4.2 Introduction

Silvicultural operations in the southeastern U.S. commonly use intensive forest management practices (Allen et al., 2005; Fox, 2000), which can be susceptible to erosion and even sedimentation if proper forestry best management practices (BMPs) are not appropriately implemented (Grace, 2005; Aust and Blinn, 2004). The Federal Water Pollution Control Act of 1972 and subsequent amendments obliged states to develop forestry BMPs to reduce the impacts of nonpoint source pollution (NPSP) associated from timber harvests (Grace, 2005; US EPA, 2005; Ice, 2004; Phillips and Blinn, 2004; Novotny, 2003). Sediment is the most prevalent source of NPSP that occurs from timber harvesting (Binkley and Brown, 1993; Yoho, 1980). Therefore, most forestry BMPs were developed to specifically address sediment and have generally been proven effective for reducing erosion and sedimentation when properly applied (Cristan et al., 2016; NCASI, 2012; Ice, 2004). Typically, timber harvests produce small quantities of erosion compared to other land uses. The EPA ranked forestry as the 10th leading cause of pollution to US rivers and streams. Forest operations were found to cause water quality problems for 7% of impaired waterways whereas agriculture was associated with 60% of

impaired streams. (US EPA, 2005; US EPA, 2000). Undisturbed mature forests in the South produce less than $0.1 \text{ ton ac}^{-1} \text{ yr}^{-1}$ of sediment while carefully clearcut forests produce less than $0.2 \text{ ton ac}^{-1} \text{ yr}^{-1}$ of sediment (Yoho, 1980). Aust and Blinn (2004) reported erosion rates in the eastern U.S. generally range between 0.1 and $4.9 \text{ ton ac}^{-1} \text{ yr}^{-1}$. Erosion from timber harvests is only a fraction of other intensive land operations such as active construction (48 to $219 \text{ ton ac}^{-1} \text{ yr}^{-1}$) (Yoho, 1980).

Timber harvests may be subdivided into different operation categories including timber harvesting, stand establishment, forest roads, skid trails, logging decks, stream crossings, and streamside management zones (SMZs). The operation categories that are most susceptible to erosion and sedimentation are forest roads, skid trails, and stream crossings (Grace, 2005; Rivenbark and Jackson, 2004; Fulton and West, 2002). Grace (2005) listed potential causes of soil erosion that occur from forest roads: (1) disruption of natural drainage, (2) exposure of bare soil, (3) alteration of natural soil structure, (4) increase of side slopes, (5) soil surface compaction that reduces infiltration, and (6) altered subsurface hydrology.

Forest water quality studies in the southeastern U.S. generally assess the effectiveness of forestry BMPs by quantifying soil erosion within operation categories (Cristan et al., 2016). The reviewed southeastern BMP studies in Cristan et al. (2016) focus on specific operation categories such as forest roads, skid trails, stream crossing approaches, and SMZs. Studies quantify erosion and sedimentation by measuring (trapping) or modeling soil loss. Modeling soil loss has been conducted by using the Universal Soil Loss Equation (USLE-Forest) (Dissmeyer and Foster, 1984), Water Erosion Prediction Project (WEPP) (Elliot and Hall, 1997), or Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). Studies may also sample stream physiochemical parameters which include total dissolved solids (TSS).

Few studies have quantified an overall timber harvest erosion rate. The majority of the studies that have been conducted evaluate specific operation categories. Wynn et al. (2000) evaluated timber harvesting BMPs in the Coastal Plain of Virginia and reported average measured sediment yields post-harvest and post-site preparation for three treatments: (1) without BMPs, (2) with BMPs, and (3) no harvest. The authors reported average sediment yields post-harvest of 4.35, 0.25, and 0.25 $\text{ton ac}^{-1} \text{yr}^{-1}$, respectively and post-site preparation of 3.42, 0.28, and 0.06, respectively. The sites that implemented BMPs resulted in a sediment yield of less than 0.3 $\text{ton ac}^{-1} \text{yr}^{-1}$. Christopher and Visser (2007) used USLE-Forest to predict an average timber harvest erosion rate for three physiographic regions (Mountains, Piedmont, and Coastal Plain) in Virginia. The authors estimated average erosion rates for the three regions to be 2, 1.2, and 1.1 $\text{ton ac}^{-1} \text{yr}^{-1}$, respectively. Barrett et al. (2016) compared estimated potential erosion rates (USLE-Forest) of conventional and biomass harvesting sites in the Virginia Piedmont and reported an average timber harvest erosion rate to be 0.8 and 0.7 $\text{ton ac}^{-1} \text{yr}^{-1}$, respectively.

There is no readily accessible database of quantified soil erosion rates from operation categories for the southeastern U.S that considers the effects of BMP implementation levels. Such a database would potentially allow development of a methodology for estimating soil erosion associated with timber harvesting. Ramos-Scharron and MacDonald (2005) used such an approach to develop a database for unpaved roads in the Virgin Islands and subsequently develop a methodology for estimating erosion from the roads. Overall, the literature indicates that a methodology for evaluating timber harvest erosion by operation categories would be useful. Therefore, this project has two basic goals: 1) to examine current (since 1999) BMP literature to develop a database of erosion rates based recent peer reviewed literature and 2) to use the

database to develop a methodology for predicting soil erosion from timber harvests with different levels of BMP implementation.

Forest organizations such as state agencies and land managers can use the database to evaluate which sites have erosion issues and might require additional BMPs. The erosion estimation method is designed to provide a rapid estimation of overall potential erosion from a specific timber harvest. This method can be used to evaluate different BMP levels. This paper focuses on the Piedmont region due to quantity of literature from that region which evaluates erosion rates by operation category.

4.3 Methods

4.3.1 Collection of Quantitative Soil Erosion Estimates

Literature pertaining to forestry BMPs in the southern U.S. that documented erosion rates from timber harvests was reviewed. Recent literature (1999-present) was the focal point due to its relevance and timeliness to current BMP practices and implementation rates. However, due to information gaps, older literature was included in the review as necessary. Three general regions were selected for the review: (1) Mountains (including Appalachian/Cumberland Plateau, Ozarks, Ouachitas, Blue Ridge, and Ridge and Valley), (2) Piedmont, and (3) Coastal Plain (Figure 9). Erosion rates from the literature were input into a Microsoft Excel spreadsheet to populate a database of erosion rates by operation category (timber harvest, forest roads, log decks, skid trails, stream approaches, stream crossings, and streamside management zones) and physiographic region.

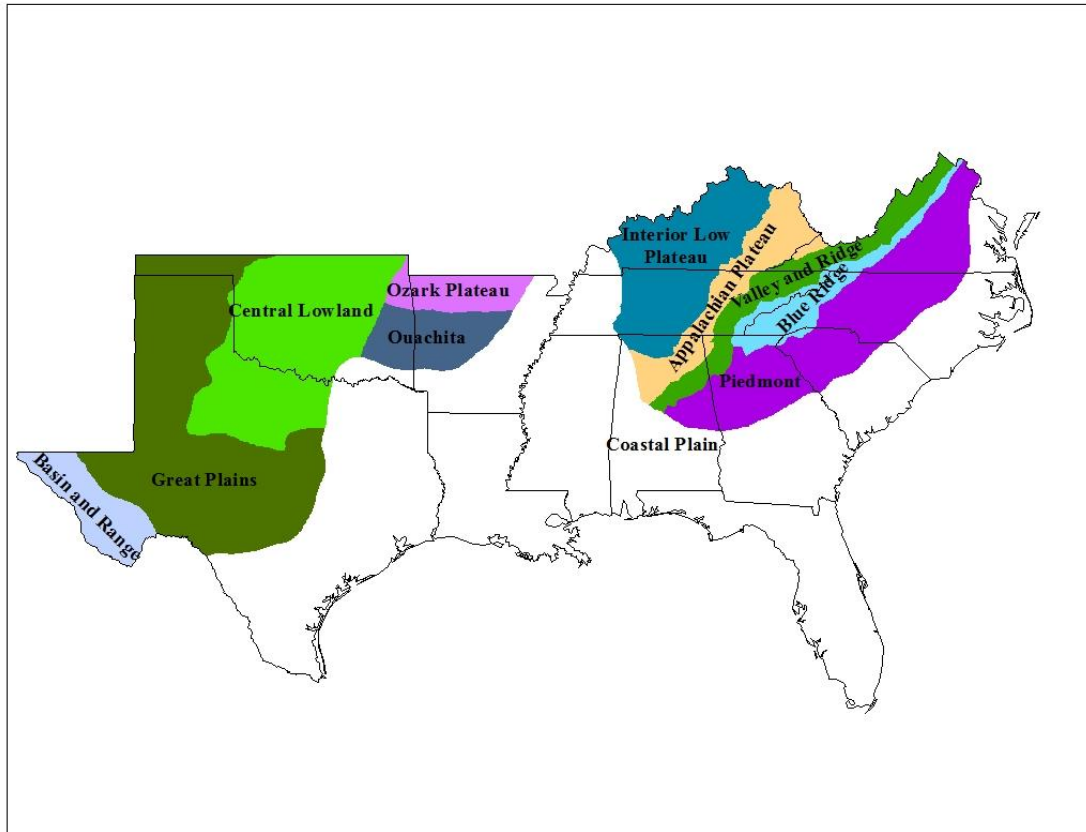


Figure 9. Physiographic regions of the southeastern U.S. The Piedmont region was selected for this study due to the availability of timber harvest research evaluating soil erosion and BMP implementation levels. Five southeastern states are located in the Piedmont region.

4.3.2 Development of Erosion Estimation Method

The erosion estimation method uses soil erosion rates obtained from peer-reviewed literature. Data limitations for the Mountain and Coastal plain regions eliminated these regions from subsequent method development, particularly for different operation categories (Table 16). Thus, the Piedmont region was the only physiographic region with literature regarding erosion rates in each operation category. The erosion estimation method was developed in a Microsoft Excel spreadsheet using the Piedmont region data (Table 17) and we elected to call this method the Virginia Tech Harvest Erosion Estimation Method (VTHEEM).

Table 16. Erosion rates with BMPs implemented for the Atlantic Coastal Plain, Gulf Coastal Plain, Piedmont, and Mountain physiographic regions of the southeastern U.S. There were 25 total studies reviewed that documented erosion rates. Erosion rates that include ranges represent different treatments and/or different BMP implementation techniques. Literature was not located (*) for many of the operation categories for the Atlantic and Gulf Coastal Plain and Mountain physiographic regions. Clearcut with stand establishment includes site preparation and/or replanting.

Operation category	Atlantic Coastal Plain	Citation	Gulf Coastal Plain	Citation	Piedmont	Citation	Mountains	Citation
	ton ac ⁻¹ yr ⁻¹		ton ac ⁻¹ yr ⁻¹		ton ac ⁻¹ yr ⁻¹		ton ac ⁻¹ yr ⁻¹	
Silvicultural treatments								
Clearcut only	*	*	*	*	0.2-0.5	1-4	0.6-4.8	5,12
Clearcut with stand establishment	0.3	6	<0.1-0.5	8-11	<0.1-0.4	1,2,7	*	*
Leave tree	*	*	*	*	*	*	4.0-5.3	5
Group selection	*	*	*	*	*	*	2.1-2.5	5
Shelterwood	*	*	*	*	*	*	1.8-2.4	5
Site preparation only	*	*	<0.1-6.3	13-15	*	*	*	*
Forest roads	*	*	*	*	<0.1-130	3-4, 16-17	*	*
Skid trails	*	*	1.4	13	0.2-61.4	3-4, 18-21	17	12
Log decks/landings	*	*	*	*	3.5-6.4	3-4	1.2	12
SMZ	*	*	<0.1	9,13	0.1	3	*	*
Stream crossings	*	*	*	*	0.9-42.7	3-4, 22-23	*	*
Firelines	*	*	2.6	13	*	*	<0.1-10.1	24
Biomass operation (overall)	*	*	*	*	0.7	3	*	*

¹1. Williams et al. (1999), 2. Fraser et al. (2012), 3. Barrett et al (2016), 4. Christopher and Visser (2007), 5. Hood et al. (2002), 6. Wynn et al. (2000), 7. Grace (2004), 8. Simpson et al. (2008), 9. Sanders and McBroom (2013), 10. McBroom et al. (2008), 11. Beasley and Granillo (1988), 12. Worrell et al. (2011), 13. Farrish et al. (1993), 14. Blackburn et al. (1986), 15. Beasley (1979), 16. Lang et al. (2016), 17. Brown et al (2013), 18. Wade et al. (2012a), 19. Wade et al. (2012b), 20. Sawyers et al. (2012), 21. Wear et al. (2013), 22. Aust et al. (2011), 23. Nolan et al (2015), 24. Christie et al. (2013).

² *. No literature found

Table 17. The Virginia Tech Harvest Erosion Estimation Method (VTHEEM) was formulated in Microsoft Excel for the Piedmont physiographic region. Users would ‘*Input*’ the area and erosion rate for each applicable operation category. Suggested erosion rates are based on the low, high, and average erosion rates obtained from the reviewed studies. Suggested erosion rates are with BMPs implemented unless ‘No BMPs’ is stated. The method ‘*Outputs*’ the total operation area (acres) and the estimated potential erosion rate (ton ac⁻¹ yr⁻¹) for a specific timber harvest.

Operation category	Operation area	Erosion rate	Suggested erosion rate
	ac	ton ac ⁻¹ yr ⁻¹	ton ac ⁻¹ yr ⁻¹
Clearcut			
Low	<i>Input</i>	<i>Input</i>	0.20 ¹
Average	<i>Input</i>	<i>Input</i>	0.34 ^{1,2,3,4}
High	<i>Input</i>	<i>Input</i>	0.48 ²
Stand establishment			
Low	<i>Input</i>	<i>Input</i>	0.06 ⁵
Average	<i>Input</i>	<i>Input</i>	0.27 ^{2,4,5}
High	<i>Input</i>	<i>Input</i>	0.37 ⁵
Forest roads			
Low	<i>Input</i>	<i>Input</i>	0.04 ⁶
Average	<i>Input</i>	<i>Input</i>	8.00 ^{1,3,6}
High	<i>Input</i>	<i>Input</i>	19.23 ⁶
No BMPs			
Low	<i>Input</i>	<i>Input</i>	32.83 ⁶
Average	<i>Input</i>	<i>Input</i>	81.26 ⁶
High	<i>Input</i>	<i>Input</i>	129.68 ⁶
Stream crossing approach			
Low	<i>Input</i>	<i>Input</i>	4.46 ⁷
Average	<i>Input</i>	<i>Input</i>	5.80 ⁷
High	<i>Input</i>	<i>Input</i>	7.14 ⁷
No BMPs			
Low	<i>Input</i>	<i>Input</i>	15.17 ⁷
Average	<i>Input</i>	<i>Input</i>	71.60 ⁷
High	<i>Input</i>	<i>Input</i>	128.03 ⁷
Stream crossing			
Low	<i>Input</i>	<i>Input</i>	1.38 ⁸
Average	<i>Input</i>	<i>Input</i>	3.93 ⁸

Skid trails	High	<i>Input</i>	<i>Input</i>	17.89 ⁸
	Overland			
	Low	<i>Input</i>	<i>Input</i>	0.54 ⁹
	Average	<i>Input</i>	<i>Input</i>	4.68 ⁹
	High	<i>Input</i>	<i>Input</i>	12.62 ⁹
Bladed	Low	<i>Input</i>	<i>Input</i>	0.36 ^{10,11}
	Average	<i>Input</i>	<i>Input</i>	12.06 ^{10,11}
	High	<i>Input</i>	<i>Input</i>	66.2 ^{10,11}
Stream crossing approach	Low	<i>Input</i>	<i>Input</i>	0.18 ¹²
	Average	<i>Input</i>	<i>Input</i>	5.58 ¹²
	High	<i>Input</i>	<i>Input</i>	17.64 ¹²
Stream crossing	Low	<i>Input</i>	<i>Input</i>	0.89 ⁸
	Average	<i>Input</i>	<i>Input</i>	5.35 ⁸
	High	<i>Input</i>	<i>Input</i>	25.38 ⁸
Decks	Low	<i>Input</i>	<i>Input</i>	3.52 ³
	Average	<i>Input</i>	<i>Input</i>	4.96 ^{1,3}
	High	<i>Input</i>	<i>Input</i>	6.40 ¹
SMZs		<i>Input</i>	<i>Input</i>	0.10 ¹
Stream crossing method	Culvert			
	Low	<i>Input</i>	<i>Input</i>	26.85 ¹³
	Average	<i>Input</i>	<i>Input</i>	34.80 ¹³
	High	<i>Input</i>	<i>Input</i>	42.74 ¹³
	Bridge			
	Low	<i>Input</i>	<i>Input</i>	17.40 ¹³
	Average	<i>Input</i>	<i>Input</i>	19.63 ¹³
	High	<i>Input</i>	<i>Input</i>	21.86 ¹³
Ford	Low	<i>Input</i>	<i>Input</i>	13.87 ¹³

Pole	Average	<i>Input</i>	<i>Input</i>	16.51 ¹³
	High	<i>Input</i>	<i>Input</i>	19.14 ¹³
	Low	<i>Input</i>	<i>Input</i>	4.10 ¹³
	Average	<i>Input</i>	<i>Input</i>	9.86 ¹³
	High	<i>Input</i>	<i>Input</i>	15.51 ¹³
Total operation area		<i>Output</i>	acres	
Estimated potential erosion rate		<i>Output</i>	ton ac ⁻¹ yr ⁻¹	

¹Barrett et al. (2016); ²Fraser et al. (2012); ³Christopher and Visser (2007);

⁴Williams et al. (1999); ⁵Grace (2004) ⁶Lang et al. (2015); ⁷Brown et al. (2013); ⁸Nolan et al. (2015); ⁹Sawyers et al. (2012); ¹⁰Wade et al. (2012)a;

¹¹Wade et al. (2012)b; ¹²Wear et al. (2013); ¹³Aust et al. (2011)

The VTHEEM was designed so that an erosion rate ($\text{ton ac}^{-1} \text{ yr}^{-1}$) and operation area (acres) could be input for each applicable operation category. The operation area is based on a timber harvest of interest and the erosion rate can be selected from the suggested erosion rates or literature database. The suggested erosion rates were based on previous studies for the Piedmont region and include low, average, and high erosions rates. Suggested erosion rates are with BMPs implemented unless ‘No BMPs’ is stated. The associated literature database is intended to help users select erosion rates based on their timber harvest.

The VTHEEM uses a weighted average of erosion for all operation categories within a timber harvest to calculate an overall estimated erosion rate for a timber harvest. After the user inputs the area and erosion rate for each applicable operation category, the total operation area and estimated potential erosion rate are calculated and output is provided. The total operation area is the sum of all applicable operation category areas. The estimated potential erosion rate multiplies each operation category area by the corresponding erosion rate to calculate an erosion rate for each operation category. Estimates of area can be based on area measurements, sources including general knowledge of the site, recent aerial imagery, or BMP audit information. Area values are summed and divided by the total operation area to obtain a potential erosion rate for a timber harvest. The equations to calculate the total operation area and estimated potential erosion rate are listed below:

$$\text{Total operation area} = \sum \text{operation area}(s)$$

$$\text{Estimated potential erosion rate} = \frac{\sum(\text{operation area} \times \text{erosion rate})}{\text{total operation area}}$$

4.3.3 Evaluation of the Erosion Estimation Method

We wished to see how well the suggested erosion rate data corresponded to field based estimates of soil erosion by comparing them with an unpublished soil erosion dataset collected from Piedmont timber harvests. USLE-forest erosion estimates were collected by Virginia Tech forestry faculty and graduate students on four timber harvests in the Virginia Piedmont. These data evaluated the following operation categories: (1) clearcut, (2) forest roads, (3) skid trails, (4) SMZs, (5) stream crossing approaches, and (6) log decks. For each timber harvest, an erosion rate was calculated using the USLE data and VTHEEM suggested erosion rates. The USLE timber harvest erosion rates were calculated using the same methods (equations) as the VTHEEM. The input variables for operation category and area remained the same for both USLE and VTHEEM for each timber harvest; however, suggested erosion rates with BMPs implemented were input. Estimated erosion rate output was compared between USLE and VTHEEM for the four timber harvests.

4.4 Reviewed Literature for the Erosion Estimation Method

Cristan et al. (2016) performed a literature review of timber harvest induced soil erosion as mitigated by BMPs for the entire United States and numerous researchers have performed similar reviews (Ice et al. (2004), Shepard (2006), Aust and Blinn (2004), Anderson and Lockaby (2011)). Our intent is not to duplicate these extensive reviews, rather our goal is to review those studies that include erosion rates for different forest operation categories in order to populate the database for the method.

4.4.1 Timber Harvesting

Forests in the Piedmont region are intensively managed and generally consist of mechanized operations (Allen et al., 2005; Fox, 2000). Five studies were reviewed that evaluated timber harvesting (clearcut) and stand establishment following timber harvesting (Table 18).

Barrett et al. (2016) and Christopher and Visser (2007) estimated erosion rates of clearcutting using USLE. The study conducted by Christopher and Visser (2007) includes 54 harvested sites throughout the three physiographic regions in Virginia while Barrett et al. (2016) includes 10 conventional harvested sites from the Virginia Piedmont. Both these studies reported similar erosion rates from clearcutting ($0.20 \text{ ton ac}^{-1} \text{ yr}^{-1}$ and $0.27 \text{ ton ac}^{-1} \text{ yr}^{-1}$, respectively).

Fraser et al. (2012) repeated a paired watershed study conducted in the 1970s in the Georgia Piedmont. The most recent study was clearcut from 2003-2004 and site prepared from 2004-2005. Georgia's 1999 BMP guidelines were applied to the site. The previous study had smaller SMZ widths and lower road runoff standards. The authors sampled suspended sediment and reported sediment loss post-harvest to be $0.48 \text{ ton ac}^{-1} \text{ yr}^{-1}$ and $0.25 \text{ ton ac}^{-1} \text{ yr}^{-1}$ for post-stand establishment (herbicide, prescribed burn, and shear blade replanting treatments).

Grace (2004) examined soil erosion from clearcutting and stand establishment techniques in the southern Piedmont of Alabama. The author evaluated erosion from (1) clearcutting and machine planting and (2) clearcutting with intensive site preparation techniques and replanting (shearing, ripping, bedding, and machine planting). The clearcut and machine planted site resulted in an erosion rate of $0.37 \text{ ton ac}^{-1} \text{ yr}^{-1}$ while the more intensive operation resulted in an erosion rate of $0.06 \text{ ton ac}^{-1} \text{ yr}^{-1}$. Grace (2004) found that the clearcut with site preparation and replanting resulted in a smaller erosion rate due to the site having a higher surface roughness

(raised beds). The author stated the experimental units were small (120 ft²) and that erosion could be affected on a larger scale.

Williams et al. (1999) evaluated suspended sediment on three watersheds in the Piedmont of South Carolina. The authors assessed erosion on three treatments: (1) clearcut only (0.4 ton ac⁻¹ yr⁻¹), (2) clearcut followed by herbicide and prescribed burn (0.29 ton ac⁻¹ yr⁻¹), and (3) clearcut followed by shearing and root raking into windrows (0.36 ton ac⁻¹ yr⁻¹). Williams et al. (1999) also noted that careful logging on upper slopes resulted in an erosion rate of 0.07 ton ac⁻¹ yr⁻¹.

Table 18. Erosion rates (ton ac⁻¹ yr⁻¹) for clearcut and stand establishment in the Piedmont physiographic region.

Silvicultural treatment	Treatment area	Average erosion rate	Citation
	ac	ton ac ⁻¹ yr ⁻¹	
Clearcut only	106	0.40	Williams et al. (1999)
	80	0.48	Fraser et al. (2012)
	15-80	0.20 ¹	Barrett (2016)
	*	0.27 ¹	Christopher and Visser (2007)
Stand establishment			
Herbicide & prescribed burn	35	0.29	Williams et al. (1999)
Shearing and root raking into windrows	12	0.36	
Sheared, ripped, bedded, and machine planting on contour	62	0.06	Grace (2004)
Machine planted on contour	62	0.37	
Herbicide, prescribed burn, and shear blade replanting	80	0.25	Fraser et al. (2012)

¹Universal Soil Loss Equation (USLE); *, No data

4.4.2 Forest Roads

Erosion can be severely accelerated during careless forest road construction; however, careful planning of forest roads can reduce impacts to water quality from erosion (Yoho, 1980). Forest roads are recognized as one of the main sources of NPS pollution from forest operations (Grace, 2005). Forest road BMPs help mitigate problems associated with erosion. Four studies evaluating erosion associated with forest roads were reviewed (Table 19). Barrett et al. (2016) reported that forest roads produced the highest average erosion ($11.80 \text{ ton ac}^{-1} \text{ yr}^{-1}$) during timber harvesting. Christopher and Visser (2007) reported a similar amount erosion from forest roads and noted that 39% of the erosion from timber harvesting is caused by forest roads in the Piedmont region.

Brown et al. (2013) assessed sediment delivery from bare and graveled forest road stream crossing approaches. The authors evaluated the effectiveness of applying gravel to forest road stream approaches on reopened legacy roads. They measured trapped sediment from five bare stream approaches and four completely graveled stream approaches. Brown et al. (2013) found graveled approaches resulted in an average erosion rate between 4.46 and $7.14 \text{ ton ac}^{-1} \text{ yr}^{-1}$ while bare approaches averaged 7.5 times more erosion (15.17 - $128.03 \text{ ton ac}^{-1} \text{ yr}^{-1}$) and concluded that properly applied (gravel and water control structures) can reduce erosion and sediment delivery. The authors also noted that erosion prediction models (USLE and WEPP) did not work well in predicting erosion rates for their sites when compared to measured trapped erosion.

Lang et al. (2015) quantified erosion from forest roads at stream crossings. The authors evaluated measured erosion of 40 forest roads in the Piedmont and Mountain regions of Virginia. They classified forest roads by rate of erosion (BMP-failure, BMP-, BMP, and BMP+). Lang et al. (2015) found that forest roads that were considered BMP failures resulted in an average

erosion rate between 32.83 and 129.68 $\text{ton ac}^{-1} \text{yr}^{-1}$. Erosion rates for forest roads considered BMP- ranged from 9.72-19.23 $\text{ton ac}^{-1} \text{yr}^{-1}$, BMP forest roads ranged from 1.61-5.62 $\text{ton ac}^{-1} \text{yr}^{-1}$, and BMP+ forest roads ranged from 0.04-1.29 $\text{ton ac}^{-1} \text{yr}^{-1}$.

Table 19. Erosion rates ($\text{ton ac}^{-1} \text{ yr}^{-1}$) for forest roads in the Piedmont region. Lang et al. (2015) classified BMP levels for different erosion rates from forest roads.

Forest operational category	Treatment area	BMP level	Average erosion rate with BMPs	Citation
	ac		$\text{ton ac}^{-1} \text{ yr}^{-1}$	
Forest roads	*	*	11.80 ¹	Barrett (2016)
	0.01-0.11	BMP-Failure	32.83-129.68	Lang et al. (2015)
	0.01-0.11	BMP-	9.72-19.23	
	0.01-0.11	BMP	1.61-5.62	
	0.01-0.11	BMP+	0.04-1.29	
Access roads	*	*	9.41 ¹	Christopher and Visser (2007)
Re-opened abandoned legacy roads				
Bare	0.01-0.10	*	15.17-128.03	Brown et al. (2013)
Graveled	0.01-0.10	*	4.46-7.14	

¹Universal Soil Loss Equation (USLE); *, No data

4.4.3 Log Decks and Landings

Research on erosion from logging decks is limited in the southeastern U.S. There were only two studies reviewed that estimated erosion from logging decks specifically in the Piedmont region (Table 20). Barrett et al. (2016) reported that logging decks only consist of a small percentage of timber harvests, but consist of the third highest erosion rate (below forest roads and skid trails) ($6.40 \text{ ton ac}^{-1} \text{ yr}^{-1}$). Christopher and Visser (2007) reported similar results in that logging decks contributed $3.52 \text{ ton ac}^{-1} \text{ yr}^{-1}$, however the authors stated that logging decks contributed 4% of the erosion rate for the Piedmont which was below access roads, clearcutting, and skid trails.

Table 20. Erosion rates ($\text{ton ac}^{-1} \text{ yr}^{-1}$) for log decks and landings in the Piedmont region.

Log decks/landings	Average erosion rate $\text{ton ac}^{-1} \text{ yr}^{-1}$	Citation
Log decks/landings	6.40^1	Barrett (2016)
	3.52^1	Christopher and Visser (2007)

¹Universal Soil Loss Equation (USLE)

4.4.4 Skid Trails

Timber harvests in the Piedmont region use both bladed and overland skid trails. Operation area of skid trails typically range from 2-10% of the total operation area (Sawyers et al., 2012). There were six studies reviewed that documented erosion rates from skid trails (Table 21). Barrett et al. (2016) predicted erosion of skid trails using USLE and reported that skid trails averaged $10.8 \text{ ton ac}^{-1} \text{ yr}^{-1}$ of erosion for timber harvests in the Piedmont region. The authors noted that skid trails produced the seconded highest erosion rate from a timber harvest (below forest roads $11.8 \text{ ton ac}^{-1} \text{ yr}^{-1}$). Christopher and Visser (2007) also used USLE to predict erosion

rates for skid trails. The authors reported that skid trail erosion rates across Virginia (including the Piedmont region) averaged $5 \text{ ton ac}^{-1} \text{ yr}^{-1}$ with skid trails representing 14% of the erosion from timber harvests in the Piedmont region (access roads and clearcutting represented 39%).

Bladed skid trails can be highly susceptible to soil erosion when BMPs are not applied properly. Wade et al. (2012a) evaluated erosion rates of five erosion control BMPs for bladed skid trails. The authors assessed five skid trail BMPs: (1) waterbar only, (2) waterbar and grass seed, (3) waterbar and hardwood slash, (4) waterbar and pine slash, and (5) waterbar, grass seed, and straw mulch. The waterbar with seed and straw mulch applied to the skid trail was the most effective BMP treatment in reducing erosion ($1.34 \text{ ton ac}^{-1} \text{ yr}^{-1}$) followed by waterbar and pine slash ($2.63 \text{ ton ac}^{-1} \text{ yr}^{-1}$), waterbar and hardwood slash ($3.97 \text{ ton ac}^{-1} \text{ yr}^{-1}$), waterbar and grass seed ($14.05 \text{ ton ac}^{-1} \text{ yr}^{-1}$), and waterbar only ($61.43 \text{ ton ac}^{-1} \text{ yr}^{-1}$). The authors found that the waterbar only treatment had a significantly higher average erosion rate than the other treatments. Wade et al. (2012b) used USLE, WEPP, and RUSLE to predict erosion rates for the same sites (Wade et al. (2012a)) and compared those predictions with measured erosion rates. The authors found that USLE performed the best due to the model incorporating cover values for forest applications and that WEPP was not properly calibrated for skid trails in the southeastern U.S. However, Wade et al. (2012b) stated that all three models were sufficient in ranking skid trail erosion rates by BMP.

Sawyers et al. (2012) assessed the effectiveness of five overland skid trail closure BMPs. The skid trail closure methods consisted of: (1) waterbar only, (2) waterbar and grass seed, (3) waterbar, grass seed, and straw mulch, (4) waterbar and hardwood slash, and (5) waterbar and pine slash. Each skid trail closure BMP was replicated on four skid trails. The authors used sediment traps to measure sediment loss and reported that the waterbar, grass seed, and mulch

BMP produced the least amount of erosion ($1.47 \text{ ton ac}^{-1} \text{ yr}^{-1}$) followed by waterbar and hardwood slash ($2.27 \text{ ton ac}^{-1} \text{ yr}^{-1}$), waterbar and pine slash ($2.41 \text{ ton ac}^{-1} \text{ yr}^{-1}$), waterbar and grass seed ($6.05 \text{ ton ac}^{-1} \text{ yr}^{-1}$), and waterbar only ($10.81 \text{ ton ac}^{-1} \text{ yr}^{-1}$). The authors also used USLE and WEPP to compare measured erosion rates with predicted erosion rates and found both USLE and WEPP followed similar trends and WEPP produced more accurate erosion predictions.

Wear et al. (2013) evaluated different BMPs on temporary skid trail stream crossing approaches. The authors predicted erosion rates with USLE for four BMPs: (1) waterbar only, (2) waterbar and slash, (3) waterbar, grass seed, and straw mulch, and (4) waterbar, grass seed, straw mulch, and silt fence. Wear et al. (2013) reported the waterbar and slash ($0.18 \text{ ton ac}^{-1} \text{ yr}^{-1}$) and waterbar, grass seed, and straw ($0.20 \text{ ton ac}^{-1} \text{ yr}^{-1}$) BMPs were the most effective at reducing erosion. The waterbar only BMP resulted in an erosion rate of $17.64 \text{ ton ac}^{-1} \text{ yr}^{-1}$. The authors found that the waterbar, grass seed, straw mulch, and silt fence BMP resulted in higher than expected erosion due to the fact the silt fences were installed too close to streams and caused soil disturbance when installed.

Table 21. Erosion rates (ton ac⁻¹ yr⁻¹) for skid trails in the Piedmont region.

Skid trails	Treatment area	Average erosion rate	Citation
	ac	ton ac ⁻¹ yr ⁻¹	
Skid trails	*	10.80 ¹	Barrett (2016)
	*	5.00 ¹	Christopher and Visser (2007)
Bladed skid trails			
Waterbar only	0.01	61.43	Wade et al. (2012)a
		28.15 ¹	Wade et al. (2012)b
		8.16 ²	
		66.20 ³	
Waterbar and seed	0.01	14.05	
		20.03 ¹	
		5.35 ²	
		6.96 ³	
Waterbar and hardwood slash	0.01	3.97	
		1.92 ¹	
		0.89 ²	
		7.81 ³	
Waterbar and pine slash	0.01	2.63	
		0.71 ¹	
		1.16 ²	
		6.91 ³	
Waterbar seed, and mulch	0.01	1.34	
		1.43 ¹	
		0.36 ²	
		1.70 ³	
Overland skid trails			
Waterbar only	0.02	10.81	Sawyers et al. (2012)
		12.62 ¹	
		10.66 ²	
Waterbar and seed	0.02	6.05	
		9.52 ¹	
		5.88 ²	
Waterbar, seed, and straw	0.02	1.47	
		0.83 ¹	

Waterbar and pine slash	0.02	0.91 ²	Wear et al. (2013)	
		2.41		
		0.54 ¹		
Waterbar and hardwood slash	0.02	2.60 ²		
		2.27		
		0.96 ¹		
		2.70 ²		
Skid trail stream approaches				
Waterbar only	*	17.64 ¹		
Waterbar and slash	*	0.18 ¹		
Waterbar, seed, straw, and silt fence	*	0.20 ¹		
Waterbar seed, and straw	*	4.28 ¹		

¹Universal Soil Loss Equation (USLE); ²Water Erosion Prediction Project (WEPP); ³Revised Universal Soil Loss Equation (RUSLE); *, No data

4.4.5 Streamside Management Zones

Streamside management zones (SMZs) are an important BMP applied along waterways. SMZs filter pollutants, uptake nutrients, increase stream bank stability, and provide shade to streams and habitat for wildlife (Lang et al., 2015; Lakel et al., 2010; Rivenbark and Jackson, 2004; Ward and Jackson, 2004). Effectiveness studies evaluating SMZs have found that SMZs effectively trap erosion which in turn reduces sedimentation (Cristan et al., 2016); however there are few SMZ studies that report sediment delivery or erosion on a yearly basis. Barrett et al. (2016) reported partially harvested SMZs average $0.10 \text{ ton ac}^{-1} \text{ yr}^{-1}$. Only two studies in the southeastern U.S. (Piedmont region) document sediment delivered to streams (sediment delivery ratio) (Lakel et al. (2010); Ward and Jackson (2004) (Table 22).

Lakel et al. (2010) assessed sediment trapping of different width SMZs. The authors evaluated four SMZ treatments on 16 watersheds that included clearcutting with stand establishment (non-intensive site preparation and replanting). The treatments consisted of three un-thinned SMZ widths (7.6 m, 15.2 m, and 30.4 m) and one thinned SMZ width (15.2 m). Lakel et al. (2010) reported that sediment delivery ratios (percentage of erosion that reached the stream) ranged from 3 to 14%. The highest sediment delivery was associated with firelines constructed near SMZs. The authors also reported SMZs stopped an average of 97% of erosion from reaching the streams.

Ward and Jackson (2004) evaluated sediment trapping and documented sediment delivery from clearcutting and stand establishment (intensive site preparation and replanting). The authors assessed SMZ effectiveness and reported SMZs trapped between 71 to 99% of sediment which is similar to the results from Lakel et al. (2010). Ward and Jackson (2004) reported a sediment delivery ratio of 25% for intensive operations in the Piedmont region.

Table 22. Erosion rates ($\text{ton ac}^{-1} \text{ yr}^{-1}$) for streamside management zones (SMZs) in the Piedmont region. Only one study reported an average erosion rate for SMZs while the other two studies reported sediment delivery ratios. Sediment delivery ratio is the amount of erosion that makes it to the stream. Sediment delivery ratios for forest operations in the Piedmont region ranged from 3 to 25%.

Streamside management zones (SMZs)	Treatment area	Average erosion rate	Sediment delivery ratio	Citation
	ac	$\text{ton ac}^{-1} \text{ yr}^{-1}$		
Partially harvested SMZs	*	0.10^1		Barrett (2016)
Non-intensive operations			0.03-0.14	Lakel et al. (2010)
7.6m SMZ	9-69	11.55 (trapped)	0.08	
15.2m SMZ	6-66	8.74 (trapped)	0.06	
15.2m thinned SMZ	8-46	11.78 (trapped)	0.08	
30.4m SMZ	5-40	12.22 (trapped)	0.08	
Intensive operations				
SMZ	246-292	*	0.25	Ward and Jackson (2004)

¹Universal Soil Loss Equation (USLE); *, No data

4.4.6 Stream Crossings

Forest road and skid trail stream crossings can have erosion issues if BMPs (water control structures and closure methods) are not implemented properly (Cristan et al., 2016). Stream crossing methods (type of crossing) can result in different erosion rates (Aust et al., 2011). Four studies evaluating erosion from stream crossings were evaluated (Barrett et al. 2016; Nolan et al. 2015; Aust et al. (2011); Christopher and Visser 2007) (Table 23).

Barrett et al. (2016) reported an estimated (USLE) erosion rate of $3.40 \text{ ton ac}^{-1} \text{ yr}^{-1}$ for temporary skidder crossings from timber harvesting. Christopher and Visser (2007) estimated (USLE) stream crossing erosion rates throughout Virginia (including Piedmont region) to be $9.28 \text{ ton ac}^{-1} \text{ yr}^{-1}$. The authors noted erosion from stream crossings represented 3% of the total weighted average erosion rate for the Piedmont region ($2.5 \text{ ton ac}^{-1} \text{ yr}^{-1}$).

Nolan et al. (2015) evaluated potential erosion rates at forest road and skid trail stream crossings. The authors classified each crossing as BMP-, BMP, and BMP+. Low standard forest road and skid trail crossings (BMP-) had an estimated erosion rate of 17.89 and $25.38 \text{ ton ac}^{-1} \text{ yr}^{-1}$, respectively. Stream crossings considered BMP- did not have adequate water control structures on the stream approaches. Forest roads and skid trail crossings with standard BMPs (BMP) had an estimated erosion rate of 3.92 and $5.35 \text{ ton ac}^{-1} \text{ yr}^{-1}$, respectively. High standard forest roads and skid trails (BMP+) resulted in an estimated erosion rate of 1.39 and $0.89 \text{ ton ac}^{-1} \text{ yr}^{-1}$, respectively.

Aust et al. (2011) assessed erosion at four different stream crossings methods (bridge, culvert, ford, and pole). The authors predicted erosion rates using USLE for different phase (initial, installation, timber harvest, closure), along with total stream crossing method erosion. Both USLE and WEPP were used to predict erosion rates. The culvert crossing resulted in the

highest total estimated erosion (42.74 and 26.85 ton ac⁻¹ yr⁻¹, respectively), followed by the bridge (17.40 and 21.86 ton ac⁻¹ yr⁻¹, respectively), ford (13.87 and 19.14 ton ac⁻¹ yr⁻¹, respectively), and pole (4.10 and 15.61 ton ac⁻¹ yr⁻¹, respectively). The authors found that water quality was affected during the installation and timber harvest phases of the operations and that the closure phase (BMPs applied) improved water quality. Aust et al. (2011) stated that BMPs should be implemented during all phases of using a stream crossing.

Table 23. Erosion rates (ton ac⁻¹ yr⁻¹) for stream crossings in the Piedmont region. Nolan et al. (2015) associated BMP levels (BMP-, BMP, BMP+) with stream crossing approaches.

Stream Crossings	Average erosion rate	Citation
	ton ac ⁻¹ yr ⁻¹	
Stream crossings	3.40 ¹	Barrett (2016)
	9.28 ¹	Christopher and Visser (2007)
Forest road stream crossings		Nolan et al. (2015)
	17.89 ¹	
	3.93 ¹	
	1.38 ¹	
Skid trail stream crossings		Nolan et al. (2015)
	25.38 ¹	
	5.35 ¹	
	0.89 ¹	
Bridge		Aust et al. (2011)
Initial	2.19 ¹	
Install	33.55 ¹	
Harvest	18.47 ¹	
Closure	15.30 ¹	
Total ¹	17.40 ¹	
Total ²	21.86 ²	

Culvert		Aust et al. (2011)
Initial	3.75 ¹	
Install	33.72 ¹	
Harvest	84.09 ¹	
Closure	49.47 ¹	
Total ¹	42.74 ¹	
Total ²	26.85 ²	
Ford		Aust et al. (2011)
Initial	2.63 ¹	
Install	9.59 ¹	
Harvest	22.97 ¹	
Closure	20.21 ¹	
Total ¹	13.87 ¹	
Total ²	19.14 ²	
Pole		Aust et al. (2011)
Initial	0.22 ¹	
Install	1.70 ¹	
Harvest	4.42 ¹	
Closure	10.13 ¹	
Total ¹	4.10 ¹	
Total ²	15.61 ²	

¹Universal Soil Loss Equation (USLE); ²Water Erosion Prediction Project (WEPP)

4.5 Erosion Estimation Method Evaluation

Evaluation of the VTHEEM was conducted by computing an estimated potential erosion rate for four timber harvests in the Virginia Piedmont (Tables 24-27). Each of the four timber harvests had USLE erosion rates and total area computed for each applicable operation category (clearcut, forest roads, skid trails, SMZs, stream approaches, and logging decks). An overall timber harvest USLE erosion rate was calculated for each timber harvest using the same equations for commuting erosion as the VTHEEM. Suggested erosion rates were then selected for input into the VTHEEM for the four timber harvests. The suggested erosion rates were either based on site features (forest roads classified as haul roads were considered to have higher erosion than graveled forest roads and closed out skid trails were considered to have lower erosion than skid trails that were not closed out) or average erosion rates determined from the reviewed studies. The output of estimated potential erosion for the four timber harvests was compared between the USLE and the VTHEEM suggested erosion rates.

The first timber harvest (site 1) was a 57.65 ac clearcut that incorporated two logging decks, forest roads (unsurfaced and graveled), and skid trail stream crossings (closed out with slash) and one skid trail and SMZ (Table 24). The total operation area was 63.8 ac. USLE estimated erosion rate for this timber harvest was $0.46 \text{ ton ac}^{-1} \text{ yr}^{-1}$ and the VTHEEM was $0.53 \text{ ton ac}^{-1} \text{ yr}^{-1}$ (difference of $0.07 \text{ ton ac}^{-1} \text{ yr}^{-1}$).

Table 24. Output of estimation timber harvest erosion using USLE erosion rates and VTHEEM suggested erosion rates for timber harvest 1 in the Virginia Piedmont. The USLE erosion rate was $0.46 \text{ ton ac}^{-1} \text{ yr}^{-1}$. The VTHEEM erosion rate was $0.53 \text{ ton ac}^{-1} \text{ yr}^{-1}$.

Operation category	Operation area	USLE erosion rate	Suggested erosion rate
	ac	$\text{ton ac}^{-1} \text{ yr}^{-1}$	
Clearcut	57.65	0.05	0.34
Forest roads			
Haul road (no gravel) (1)	0.26	21.88	19.23
Gravel road (1)	0.14	6.98	8.00
Decks (2)	1.40	14.17	4.96
Skid trail			
Overland (1)	0.09	0.04	4.68
Stream approaches (2)	0.11	0.10	5.58
SMZs (1)	4.15	0.03	0.10
Total operation area	63.80	ac	
Erosion estimation method	0.53	$\text{ton ac}^{-1} \text{ yr}^{-1}$	
USLE	0.46	$\text{ton ac}^{-1} \text{ yr}^{-1}$	

The second timber harvest was a 36.23 ac clearcut that consisted of one log deck, bladed skid trail, and haul road and two stream crossing approaches (Table 25). The two stream crossing approaches were not closed out. Total operation area was 44.3 ac. USLE estimated erosion was 0.85 ton ac⁻¹ yr⁻¹ while the VTHEEM was 0.64 ton ac⁻¹ yr⁻¹ (difference of 0.21 ton ac⁻¹ yr⁻¹).

Table 25. Output of estimation timber harvest erosion using USLE erosion rates and VTHEEM suggested erosion rates for timber harvest 2 in the Virginia Piedmont. The USLE erosion rate was 0.85 ton ac⁻¹ yr⁻¹. The VTHEEM erosion rate was 0.61 ton ac⁻¹ yr⁻¹.

Operation category	Operation area	USLE erosion rate	Suggested erosion rate
	ac	ton ac ⁻¹ yr ⁻¹	
Clearcut	36.23	0.11	0.34
Forest roads (haul road) (1)	0.27	59.89	19.23
Decks (1)	0.22	5.77	4.96
Skid trails			
Bladed (1)	0.36	42.84	19.28
Stream approaches (not closed out) (2)	0.13	7.80	17.64
SMZs	7.09	0.00	0.10
Total operation area		44.30	ac
Erosion estimation method		0.64	ton ac ⁻¹ yr ⁻¹
USLE		0.85	ton ac ⁻¹ yr ⁻¹

The third timber harvest was a 122.5 ac clearcut that incorporated one overland skid trail, two log decks, haul roads, and SMZs, and eight stream crossing approaches (Table 26). The stream approaches were closed out using grass seed, straw mulch, and fertilizer (2), grass seed, straw mulch, and silt fence (2), or slash (4). The erosion rate for timber harvest 3 using USLE was calculated to be $0.14 \text{ ton ac}^{-1} \text{ yr}^{-1}$ and $0.41 \text{ ton ac}^{-1} \text{ yr}^{-1}$ using the VTHEEM with a difference of $0.27 \text{ ton ac}^{-1} \text{ yr}^{-1}$.

Table 26. Output of estimation timber harvest erosion using USLE erosion rates and VTHEEM suggested erosion rates for timber harvest 3 in the Virginia Piedmont. The USLE erosion rate was $0.14 \text{ ton ac}^{-1} \text{ yr}^{-1}$. The VTHEEM erosion rate was $0.41 \text{ ton ac}^{-1} \text{ yr}^{-1}$.

Operation category	Operation area	USLE erosion rate	Suggested erosion rate
	ac	$\text{ton ac}^{-1} \text{ yr}^{-1}$	
Clearcut	122.50	0.06	0.34
Forest roads (haul road) (2)	0.40	19.55	19.23
Decks (2)	0.30	11.22	4.96
Skid trails			
Overland (1)	0.36	0.45	4.68
Stream approaches (8)	0.28	0.10	5.58
SMZs (2)	9.16	0.01	0.10
Total operation area	133.00	ac	
Erosion estimation method	0.41	$\text{ton ac}^{-1} \text{ yr}^{-1}$	
USLE	0.14	$\text{ton ac}^{-1} \text{ yr}^{-1}$	

The last timber harvest (31.15 ac) included one logging deck, skid trail, haul road, and SMZ (Table 27). The timber harvest also had two closed out stream crossing approaches (grass seed, straw mulch, fertilizer, and silt fence). The total operational area was 33.7 ac. The erosion rates estimated using USLE and the VTHEEM for timber harvest four had the greatest difference between the methods ($0.54 \text{ ton ac}^{-1} \text{ yr}^{-1}$) with USLE predicting 1.18 and the VTHEEM predicting $0.64 \text{ ton ac}^{-1} \text{ yr}^{-1}$.

Table 27. Output of estimation timber harvest erosion using USLE erosion rates and VTHEEM suggested erosion rates for timber harvest 4 in the Virginia Piedmont. The USLE erosion rate was $1.18 \text{ ton ac}^{-1} \text{ yr}^{-1}$. The VTHEEM erosion rate was $0.64 \text{ ton ac}^{-1} \text{ yr}^{-1}$.

Operation category	Operation area	USLE erosion rate	Suggested erosion rate
	ac	$\text{ton ac}^{-1} \text{ yr}^{-1}$	
Clearcut	31.15	1.14	0.34
Forest roads (haul road) (1)	0.51	7.92	19.23
Decks (1)	0.12	2.81	4.96
Skid trails			
Overland (1)	0.03	1.12	4.68
Stream approaches (2)	0.06	0.12	5.58
SMZs (1)	1.83	0.00	0.10
Total operation area	33.70	ac	
Erosion estimation method	0.64	$\text{ton ac}^{-1} \text{ yr}^{-1}$	
USLE	1.18	$\text{ton ac}^{-1} \text{ yr}^{-1}$	

4.6 Discussion

The literature review of forest erosion and sedimentation studies found information deficiencies in quantitative soil erosion studies conducted in the southeastern U.S (Table 16). The Piedmont physiographic region was the only region that included quantitative soil erosion literature (1999-present) for nearly all operation categories reviewed (13 studies), but firelines were missing within this region. Reviewed literature was dated and/or limited in the other three regions (Atlantic Coastal Plain, Gulf Coastal Plain, and Mountains). The dated literature in some cases does not reflect current harvest practices. The Atlantic Coastal Plain had the fewest relevant studies (1 study) followed by the Mountain region (3 studies), and Gulf Coastal Plain (7 studies).

The VTHEEM was developed for timber harvests conducted in the Piedmont region due to the deficiencies in the other physiographic regions. Sufficient data were available for review to provide erosion rates for all operation categories but firelines, although this region would also benefit from additional information. Suggested erosion rates (low, average, and medium) were based off documented erosion rates from the reviewed literature. Quantitative erosion studies were limited for SMZs (1) and log decks (2).

Timber harvest erosion rates were compared between the VTHEEM and USLE for four timber harvests in Piedmont region of Virginia. Overall, the VTHEEM predicted similar timber harvest erosion rates as the USLE field collected erosion estimates. The average weighted timber harvest erosion rate using the USLE data ranged from 0.1 to 1.2 ton ac⁻¹ yr⁻¹ across the four timber harvests with an average erosion rate of 0.7 ton ac⁻¹ yr⁻¹ while the average weighted erosion rate using the VTHEEM ranged from 0.4 to 0.6 ton ac⁻¹ yr⁻¹ with an average erosion rate of 0.6 ton ac⁻¹ yr⁻¹. The average erosion rate of 0.6 ton ac⁻¹ yr⁻¹ predicted using the VTHEEM was

similar to the $0.8 \text{ ton ac}^{-1} \text{ yr}^{-1}$ that Barrett et al. (2016) estimated from 10 timber harvests in the Virginia Piedmont. Christopher and Visser (2007) estimated a slightly higher average timber harvest erosion rate of $1.2 \text{ ton ac}^{-1} \text{ yr}^{-1}$ over 18 Piedmont sites. These comparisons of the literature derived erosion rates versus field estimates of soil erosion (USLE) indicate that the VTHEEM works well for estimating soil erosion, yet further comparisons across a range of conditions and BMP levels is desirable.

4.7 Conclusions

Overall erosion rate outputs for the VTHEEM were similar to the USLE field collected erosion rates. The majority (13) of the 24 reviewed studies were conducted in the Piedmont physiographic region. The VTHEEM might be used to estimate erosion from timber harvests in the Atlantic and Gulf Coastal Plain and Mountain regions; however, the VTHEEM would not be as accurate because of data gaps.

The literature reviewed from the Mountain region focused on several operation categories; however, there is a limited number of studies with no recent studies evaluating forest roads, stream crossings and SMZs. The Gulf Coastal Plain had the second most reviewed studies on erosion, however, several of the studies (4) are dated. Research for this region needs to be focused on all operation categories but stand establishment. The Atlantic Coastal Plain is the most deficient region in quantitative research on erosion from timber harvesting. Even though the Piedmont region included literature from most of the operation categories to complete the VTHEEM, further research is needed to make the method more accurate. Erosion studies on firelines are lacking in the Piedmont region, along with limited erosion literature on SMZs, stream crossing methods, and log decks.

This methodology is intended to serve as an aid to land managers tasked with deciding where to apply limited BMP resources in order to better control soil erosion and protect water quality; however, it is not appropriate for use to determine an actual erosion rate (VTHEEM estimates erosion). Overall conclusions from the literature review and the VTHEEM include:

- There are relatively few areas that have sufficient erosion data sets that reflect the expected erosion that occurs from different operation categories within a timber harvest and even fewer predictions of sediment delivery ratios, thus the VTHEEM may prove difficult to implement in other regions (weakness of the methodology). Additional quantification of erosion rates and sediment delivery ratios are needed;
- There are not well developed relationships between BMP implementation rates and erosion. Although numerous studies have shown that an overall application of forestry BMPs minimizes both erosion and sedimentation, there are few studies that actually document how a range of BMPs relates to soil erosion. Such information is needed in order to expand the utility of the existing information as well as the implementation of the VTHEEM.

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5.0 CONCLUSIONS

This dissertation consisted of three manuscripts: (1) Effectiveness of forestry best management practices in the United States: literature review, (2) National status of state developed and implemented forestry best management practices in the United States, and (3) A method for predicting potential forest harvesting induced erosion rates with different levels of BMPs. The objective of the first manuscript was to conduct a literature review of forestry BMPs in the U.S. Eighty-one BMP effectiveness studies from the Northern, Southern, and Western regions of the U.S. were reviewed. The objective of the second manuscript was to survey state forestry agencies in the U.S on the status of their BMP programs. This survey provided updated information regarding state BMP programs and allowed for comparison of BMP implementation data between state regulation (non-regulatory, quasi-regulatory, and regulatory) and region of the U.S. The third manuscript objectives were to review literature that quantified soil erosion rates from timber harvests in the southeastern U.S., develop a database from the reviewed literature, and develop a method for estimating erosion that occurs from timber harvesting. Overall, 24 studies were reviewed that quantified soil erosion rates associated with timber harvesting.

Literature reviews on BMP effectiveness studies have been done in the past, however; these reviews were region specific and focused on broader categories (timber harvesting, site preparation, and biomass harvesting) while this review focused on the entire U.S. and specific operation categories (timber harvesting, skid trails, forest roads, streamside management zones, site preparation, etc.). This review provides documentation on forestry BMP effectiveness studies so that forest managers and agency personnel could have current information on BMP efficacy in different operation categories. Even though BMP effectiveness studies are site and region specific, they have one similar outcome in that forestry BMPs minimize water quality

impacts from timber harvesting when they are implemented correctly as state guidelines recommend.

BMP effectiveness studies provide states with information on how their state BMP guidelines are complying with the goals of the Federal Water Pollution Control Act and its subsequent amendments. The literature review found that these studies often report that forest roads, skid trails, and stream crossings are the most susceptible areas of erosion and sediment delivery from timber harvesting. Some key findings from the literature review include: (1) BMPs reduce erosion when properly applied, (2) pre-harvest planning and involving a professional forester can help locate areas of concern, (3) streamside management zones are effective in trapping erosion, (4) sediment control and drainage structures help reduce runoff and sediment delivery, (5) skid trails need to be closed out with proper closeout practices, and (6) increased emphasis should be placed on the application of BMPs during all phases of a timber harvest, not just at closeout.

There have been few forestry BMP implementation studies on a national scale. The BMP survey conducted in this dissertation was similar to surveys conducted in the past; however, the most recent survey was conducted in 2004. Respondents from all 50 states completed the survey. This survey provided an updated assessment of state BMP programs and allowed for evaluation between BMP implementation and state regulation and region. Several areas of state BMP programs were addressed: (1) BMP manual and date, (2) state regulation, (3) legislation and policy, (4) implementation data, (5) effectiveness studies, (6) BMP monitoring, (7) agency(s) involved, and many others.

Every state reported having a BMP manual or guidelines with 48 states having online access to their manual or guidelines. State BMP regulations vary by state and region with 20

states consisting of non-regulatory BMP guidelines, 19 quasi-regulatory guidelines, and 11 regulatory guidelines. BMP guidelines were primarily non-regulatory and quasi-regulatory in the southeast, quasi-regulatory and regulatory in the northeast and lake states, non-regulatory in the central and north central U.S., and regulatory for the Pacific Coast States. The national BMP implementation rate was 91% (32 states) which was similar to the 2004 study of 91% (27 states). No significant differences were found between state BMP regulation and BMP implementation rate (overall state rate and individual BMP category rates) However, there were significant differences between region of the U.S. for overall state BMP implementation, timber harvesting, skid trails, stream crossings, and SMZs. The northeastern region resulted in the lowest mean BMP implementation rate in all these cases. This could be related to the implementation strategy set in place by the Northeastern Area Association of State Foresters.

Forestry BMP implementation rates were found to be high overall; however, several deficiencies were detected when evaluating individual BMP categories. These deficiencies are not revealed when assessing the overall state implementation rate due to several individual BMP categories being averaged to calculate an overall implementation rate. Strategies and procedures on determining the implementation of forestry BMPs vary by region and state. These strategies may need to be evaluated in the future to adjust for these deficiencies so that they could be better reflected in the state's overall BMP implementation rate.

The forestry BMP literature reviewed for the Virginia Tech Harvest Erosion Estimation Method (VTHEEM) overlapped some of the studies reviewed in the BMP effectiveness study literature review; however, this study was specifically assessing quantitative soil erosion rates from timber harvesting. This study was on a regional scale (southeast) compared to the first two studies in this dissertation. Recent literature (1999- present) that quantified soil erosion

associated with timber harvesting were reviewed for four physiographic regions in the southeastern U.S. (Mountains, Piedmont, Gulf Coastal Plain, and Atlantic Coastal Plain). Literature was insufficient for all the physiographic regions in the southeast except the Piedmont region. The reviewed studies in the Piedmont region included all operation categories of interest, except firelines (clearcutting, skid trails, forest roads, log decks, SMZs, and stream crossings). Due to the insufficient data, only the Piedmont region was used to formulate the VTHEEM.

Field based soil erosion estimates using USLE were compared to the VTHEEM output erosion rates for four timber harvests in the Piedmont. The VTHEEM predicted erosion rates were found to be similar to the USLE erosion rates. This method is intended to be a simple, yet useful tool that forest managers can use to estimate potential forest operation erosion with different levels of BMP treatments. However, there are still some major gaps and weaknesses in this methodology. The erosion data are limited for the Piedmont region and there is not enough data to formulate this method for the other southeastern physiographic regions. Another area of concern is the limited number of sediment delivery studies that identify how much erosion is actually delivered to streams.

Overall, these three manuscripts have supported the premise that forestry BMPs reduce impacts to water quality when they are applied properly and sufficiently. BMP effectiveness studies have helped states identify water quality issues from forest operations. They also allow for the evaluation of different BMP treatments and levels of application. These studies have found erosion rates to be significantly lower when BMPs are applied. The national BMP implementation rate is also above 90% which indicates that BMPs are being implemented; however, state BMPs are monitored differently.

However, several future research needs and gaps were identified from this study. BMP implementation data collection and reporting strategies may need to be evaluated to identify potential deficiencies from BMP implementation studies. The third manuscript chapter found several research gaps in quantitative soil erosion studies. Research studies in the southeastern U.S. need to focus additionally on evaluating sediment delivery ratios from forest operations. Another key future research goal would be to link BMP implementation rates to soil erosion rates. This would provide pivotal information on estimating the quantity of erosion that occurs following different rates of BMP implementation. Linking BMP implementation rates to soil erosion rates could assist state agencies in identification of weaknesses in BMP guidelines if high implementation scores are not resulting in lower erosion losses. However, this would most likely need to be state or physiographic region specific for it to be an effective measure. Forestry BMPs have evolved over time due to forestry BMP effectiveness studies and will continue to evolve as additional information becomes available to help land managers meet water quality goals.

This research project reviewed BMP effectiveness studies from across the U.S. and assessed state forestry BMP programs. Key findings associated with forestry BMPs and their importance in protecting water quality were revealed in the manuscripts. The overall key findings include.

- More states are conducting implementation studies (32) than in the past (27). However, further research is needed to link erosion with rates of BMP implementation and also to link BMP implementation with forest certification programs;
- BMP implementation study protocols differ by region or state of the U.S. Implementation rates for the northeastern region were significantly lower than the southeastern and western regions which indicates that implementation rates could be lower due to the

northeastern implementation protocol, landownership, topography, soils, or timber harvesting systems;

- No significant differences were found between mean state BMP implementation and state BMP regulation (non-regulatory, quasi-regulatory, and regulatory). This indicates that state BMP regulation does not have an effect on state implementation rates;
- BMP effectiveness studies are important because they provide states with evidence on whether their states BMP guidelines are meeting water quality goals of the Federal Water Pollution Control Act. The number of studies that have been conducted throughout the U.S. on BMP effectiveness also indicates the importance of these studies;
- BMP effectiveness studies have quantified erosion associated with timber harvesting. However, there were only two studies reviewed that quantified sediment delivery to streams. Sediment delivery is important because it is the amount of erosion that actually makes it to the streams which in turn affects water quality;
- The review of southeastern timber harvest erosion studies found several deficient operation categories for all of the physiographic regions (Mountains, Piedmont, Atlantic Coastal Plain, and Gulf Coastal Plain). The Piedmont region was the least deficient; however, this region was limited in quantitative erosion data for log landings, firelines, and stream crossings. Quantitative soil erosion studies need to be addressed in the future for timber harvests in the Mountain and Coastal Plain regions so that there will be a better understanding of erosion associated from timber harvesting in these regions with the possibility of relating BMP implementations rates to erosion rates.