Forest Ecology and Management 360 (2016) 133–151

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Review and synthesis

Effectiveness of forestry best management practices in the United States: Literature review

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ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 14 October 2015
Accepted 15 October 2015
Available online 26 October 2015

Keywords:
Forestry best management practices (BMPs)
BMP effectiveness studies
Water quality
Sediment delivery
Erosion
Forest operations

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. 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.

Contents

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http://dx.doi.org/10.1016/j.foreco.2015.10.025
0378-1127/© 2015 Published by Elsevier B.V.

1. 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 non-point 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, 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. 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

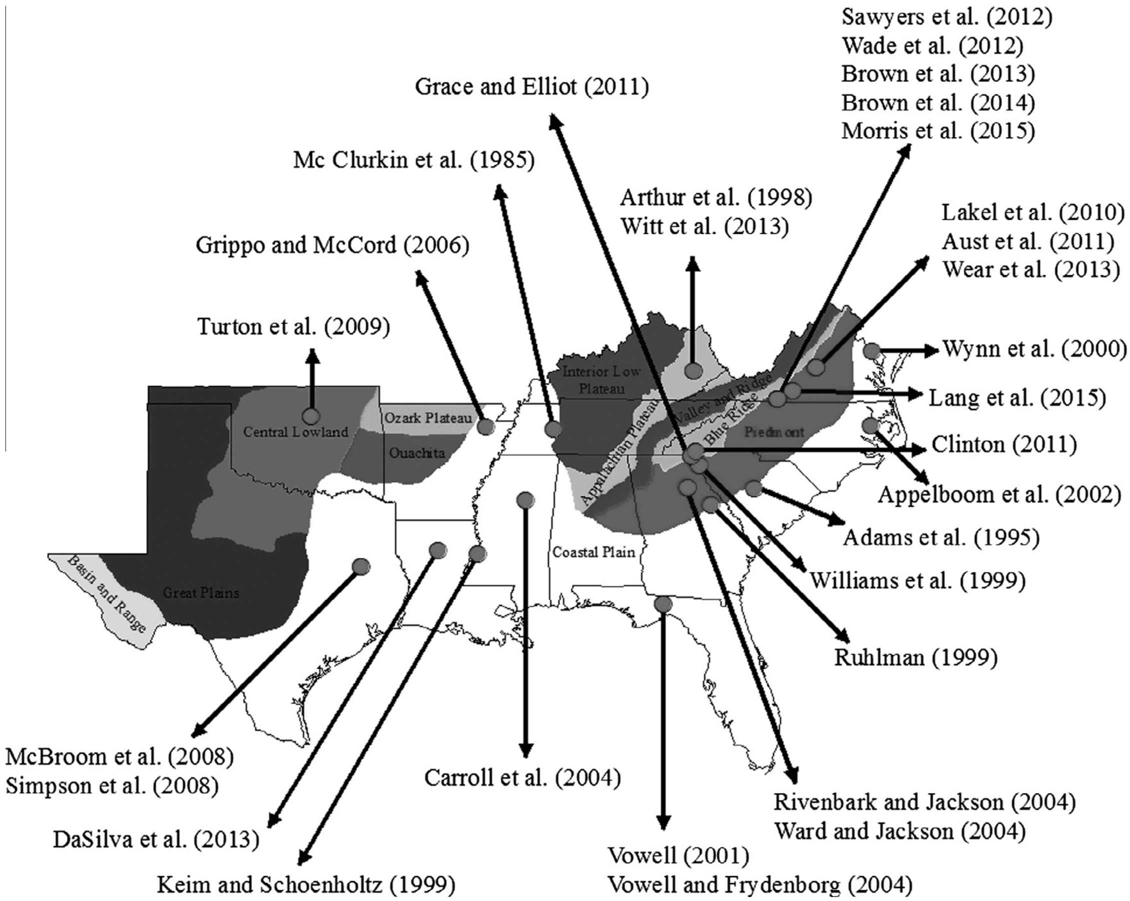

Fig. 1. Reviewed BMP effectiveness studies by state and physiographic region for the southeastern United States. Locations were determined from the studies as well as Schilling and Ice (2012).

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.

2.1. Southern states

Thirty BMP effectiveness studies from 1985 to 2015 were reviewed and documented by state and physiographic region for the Southern US (Fig. 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).

2.1.1. 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).

2.1.1.1. 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

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
Grippo 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% and 97% of the erosion

Table 1 (*continued*)

Investigators	Region/location	Study conducted by	Evaluations/treatments	Major conclusions
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 Mg ha^{-1} y^{-1}) was the most effective method in reducing erosion followed by hardwood slash (5.1 Mg ha^{-1} y^{-1}), pine slash (5.4 Mg ha^{-1} y^{-1}), seed (13.6 Mg ha^{-1} y^{-1}), and control (24.2 Mg ha^{-1} 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 (34–287 Mg ha^{-1} y^{-1}) than the gravel road approaches (10–16 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

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.

Grippo 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.

2.1.1.2. 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 2773 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.

2.1.1.3. Forest roads. Forest roads tend to be one of the major sources of sediment from forest operations. Appelboom 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). Appelboom 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 (34–287 Mg ha^{-1} y^{-1}) than graveled road approaches

(10–16 Mg ha^{-1} 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.

2.1.1.4. 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 Mg ha^{-1} y^{-1}) followed by waterbar with hardwood slash (5.1 Mg ha^{-1} y^{-1}), waterbar with pine slash (5.4 Mg ha^{-1} y^{-1}), waterbar with seed (13.6 Mg ha^{-1} y^{-1}), and waterbar only (24.2 Mg ha^{-1} 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 Mg ha^{-1} y^{-1}) followed by waterbar with pine slash (5.9 Mg ha^{-1} y^{-1}), waterbar with hardwood slash (8.9 Mg ha^{-1} y^{-1}), waterbar with seed (31.5 Mg ha^{-1} y^{-1}), and waterbar only (137.7 Mg ha^{-1} 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.

2.1.1.5. 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: 0.5–1.0 in. per hour, medium: 1.5–2.0 in. per hour, and high: 2.0–2.5 in. 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.

2.1.2. 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.

2.1.3. 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.

2.1.4. Industry

We reviewed 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.

2.2. Northern states

BMP effectiveness studies in the northern US take place primarily in the northeastern and lake state regions (Fig. 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).

2.2.1. Academia

2.2.1.1. 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 Corbett (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 Corbett (1990) concluded that BMPs were effective due to no serious altercations of water quality and suggested buffer strips on intermittent streams, increases in buffer strip width, and post-harvest site inspections.

Paashaus 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,

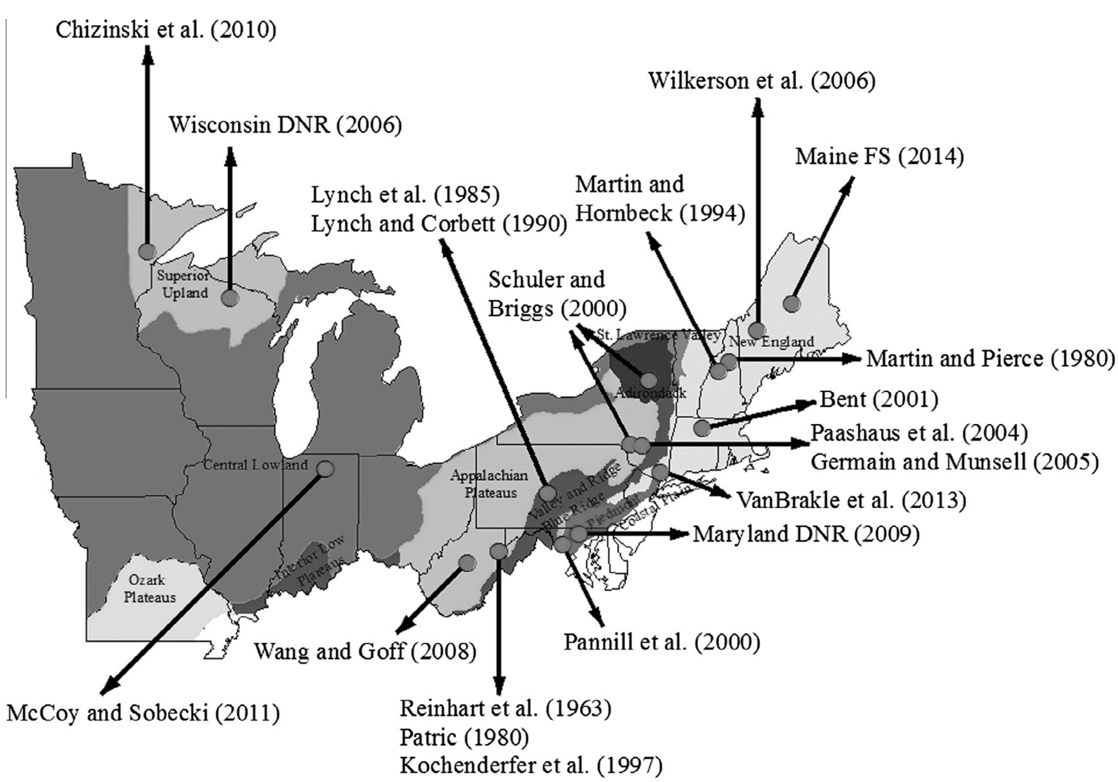

Fig. 2. Reviewed BMP effectiveness studies by state and physiographic region for the northern United States. Locations were determined from the studies as well as Schilling and Ice (2012).

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 to 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

(*continued on next page*)

Table 2 (*continued*)

Investigators	Region/location	Study conducted by	Evaluations/treatments	Major conclusions
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 to 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

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.

2.2.1.2. 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.

2.2.2. 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.

2.2.3. 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.

2.2.4. 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.

2.3. Western states

BMP effectiveness studies in the Western US focus primarily on the Pacific Border physiographic region where forest operations are most prevalent (Fig. 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).

2.3.1. Academia

2.3.1.1. 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.

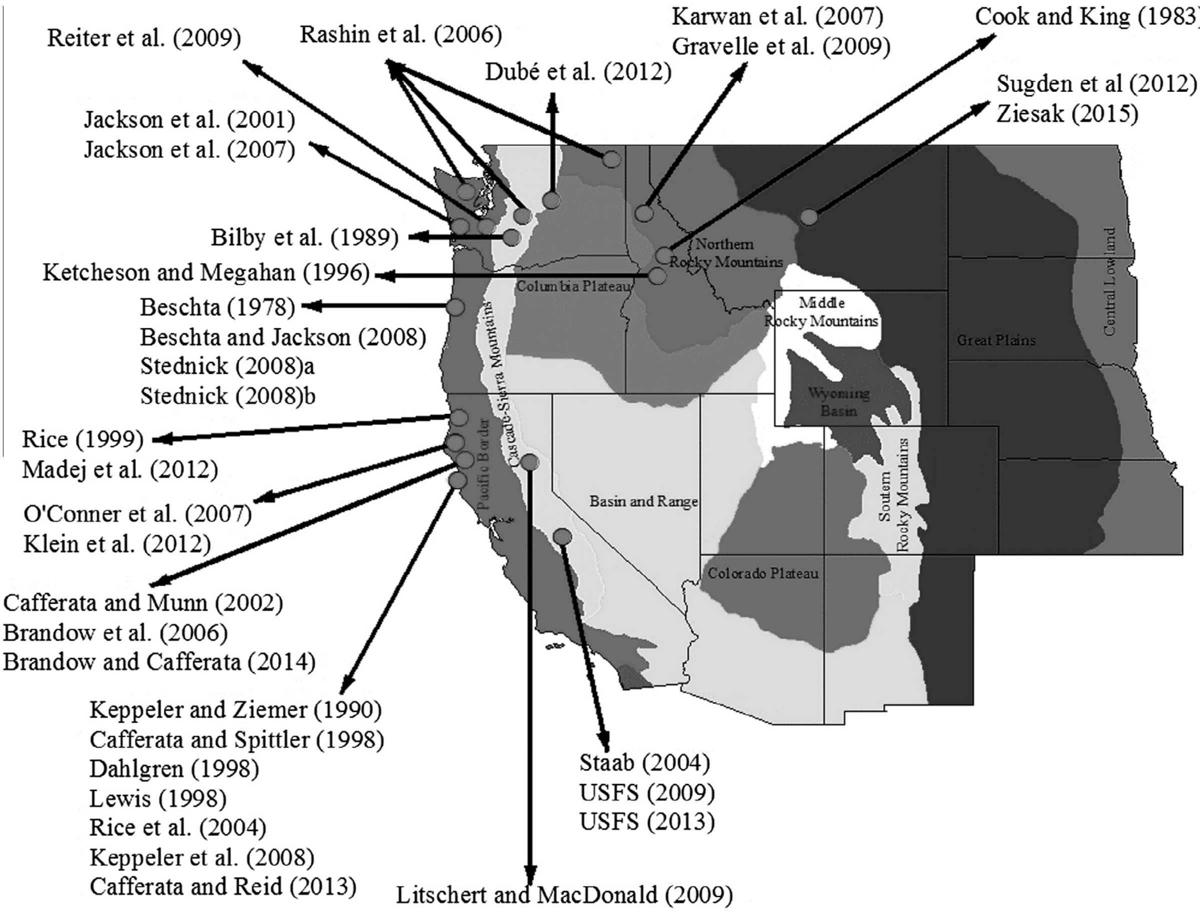

Fig. 3. Reviewed BMP effectiveness studies by state and physiographic region for the western United States. Locations were determined from the studies as well as Schilling and Ice (2012).

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 to 1997 (pre-harvest and pre-road construction/improvement), 1998 to 2001 (post-road construction/improvement), and 2001 to 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.

2.3.1.2. 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, (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.

2.3.1.3. 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.

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 m^3 ha^{-1} $yr^{-1}$and intensive erosion control practices for road construction resulted in an average erosion rate of 17.1 m^3 ha^{-1} 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, (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 threefold 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 habitat conditions	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 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

(*continued on next page*)

Table 3 (*continued*)

Investigators	Region/location	Study conducted by	Evaluations/treatments	Major conclusions
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'Connor 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 and 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 to 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

Table 3 (*continued*)

Investigators	Region/location	Study conducted by	Evaluations/treatments	Major conclusions
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 deceased 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 deceased 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 (2014)	California	State	Evaluated California's FPRs implementation and effectiveness from 2008 to 2013; Coast, Cascade, and Sierra Regions	Implementation of FPRs were high and effective in preventing 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

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.

2.3.2. Federal

2.3.2.1. 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 75–95% 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 1970s to the 1990s. Two treatment watersheds (North Fork and South Fork) were compared. South Fork roads were constructed in the 1960s and located near stream channels. This watershed was selectively harvested using tractors in the 1970s. 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 1475 kg ha^{-1} yr^{-1} and 2877 kg ha^{-1} 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'Connor 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'Connor 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.

2.3.2.2. 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 kg N ha^{-1} yr^{-1} loss post-harvest and less than 0.4 kg N ha^{-1} yr^{-1} three years post-harvest. The control watershed for the same period resulted in a nitrogen loss less than 0.1 kg N ha^{-1} 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 2237 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.

2.3.3. State

2.3.3.1. 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.

2.3.3.2. 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 (2014) 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.

2.3.4. 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.

2.3.5. 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 $m^3 km^{-1}$ 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.

2.3.6. 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.

3. 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:

3.1. 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.

3.2. 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.

Acknowledgements

Funding for this research was provided by the National Association of State Foresters, the Sustainable Forestry Initiative, Virginia Agricultural Experiment Station, the Department of Forest Resources and Environmental Conservation of Virginia Tech, and the MacIntire-Stennis Program of the National Institute of Food and Agriculture, United States Department of Agriculture.

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