NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

ASSESSING THE EFFECTIVENESS OF CONTEMPORARY FORESTRY BEST MANAGEMENT PRACTICES (BMPs): FOCUS ON ROADS

SPECIAL REPORT NO. 12-01
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PRESIDENT'S NOTE

NCASI works with member companies and others to find practical solutions to environmental issues. For example, NCASI has been testing and documenting the effectiveness of forestry best management practices (BMPs) for water quality protection since the 1970s.

Today, forestry professionals generally recognize BMPs as effective core elements of forestry nonpoint source control programs. Nevertheless, some stakeholders are challenging the effectiveness of forestry BMPs in context of legal proceedings such as *NEDC v. Brown* – a case in which the U.S. Court of Appeals for the Ninth Circuit has ruled that some forest roads are subject to "point source" permit requirements of the Clean Water Act. The U.S. Supreme Court is considering two petitions seeking review of the Ninth Circuit's decision.

This Special Report summarizes hundreds of studies that confirm the effectiveness of forestry BMPs generally and BMPs for forest roads in particular. For example:

- Long-term, basin-wide monitoring studies show improving trends in water quality associated with implementation of forestry BMPs.
- Paired watershed studies in Georgia, Texas, and Oregon have shown that sediment loads from contemporary forestry practices are reduced by 80% or more compared to past practices.
- Many research projects have tested the effectiveness of specific BMPs for forest roads. Several studies have shown that disconnecting road drainage structures from streams can reduce effects of forest road systems on sediment loads and peak flows. Efforts to disconnect forest roads from streams are ongoing and have already produced substantial reductions in metrics of connectivity.
- A recent survey of active forestry operations in Montana found that roads had been upgraded at 50% of sites assessed, thus reducing potential for sediment movement to streams.

In total, there is strong evidence that forestry BMPs work, that there are effective BMPs for forest roads, and that the forest community is implementing BMPs and providing enhanced water quality protection.

Ronald A. Yeske

January 2012

MOT DU PRÉSIDENT

NCASI travaille en collaboration avec ses sociétés membres et d'autres partenaires afin de trouver des solutions pratiques à des problèmes de nature environnementale. Par exemple, NCASI teste et documente l'efficacité des meilleures pratiques d'aménagement forestier (MPAF) en matière de protection de la qualité de l'eau.

De nos jours, les professionnels de la foresterie reconnaissent que les MPAF constituent généralement des éléments clés efficaces des programmes de contrôle de la pollution diffuse en forêt. Néanmoins, certains parties prenantes contestent l'efficacité des MPAF dans le cadre de procédures judiciaires telles que la cause *NEDC v. Brown* – une cause dans laquelle la Cour d'appel du neuvième circuit aux États-Unis a statué que certains chemins forestiers sont assujettis aux exigences sur les sources ponctuelles inscrites dans les permis, et ce, en vertu du *Clean Water Act*. La cour suprême des États-Unis examine actuellement deux demandes de révision de la décision de la Cour d'appel.

Le présent rapport spécial est une synthèse de centaines d'études qui confirment l'efficacité des MPAF en général et, plus particulièrement, l'efficacité de celles qui s'appliquent aux chemins forestiers. Par exemple :

- Les études de suivi à long terme à l'échelle des bassins montrent une tendance à l'amélioration en matière de qualité de l'eau associée à la mise en œuvre des MPAF.
- Les études de bassins versants appariés réalisées dans les États de la Georgie, du Texas et de l'Oregon ont montré que la charge en sédiments associée aux pratiques forestières modernes a diminué de 80% et plus comparativement à la charge associée aux pratiques passées.
- Dans de nombreux projets de recherche, on a testé l'efficacité de MPAF qui s'appliquent spécifiquement aux chemins forestiers. Plusieurs études ont montré qu'il est possible de réduire les effets du réseau de chemins forestiers sur la charge en sédiments et sur les débits de pointe en ne reliant plus les structures de drainage de ces chemins à un cours d'eau. Les travaux dans ce domaine se poursuivent, mais ont déjà donné lieu à d'énormes réductions dans les paramètres de connectivité.
- Une récente enquête sur les activités forestières en cours dans l'État du Montana a révélé qu'on avait amélioré les chemins dans 50% des sites évalués, ce qui réduisait la possibilité que les sédiments soient acheminés dans un cours d'eau.

Il y a donc de fortes indications que les MPAF donnent des résultats, qu'il existe des MPAF efficaces pour les chemins forestiers et que l'industrie forestière met effectivement en œuvre des MPAF et prend davantage de mesures pour protéger la qualité de l'eau.

Ronald A. Yeske

Janvier 2012

ASSESSING THE EFFECTIVENESS OF CONTEMPORARY FORESTRY BEST MANAGEMENT PRACTICES (BMPs): FOCUS ON ROADS

SPECIAL REPORT NO. 12-01
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ABSTRACT

There is a long history of research on the effects of forest management on water resources. Results have supported development and continuous improvement of best management practices (BMPs) for controlling effects of forestry operations on water quality and beneficial uses. This report summarizes research on the effectiveness of BMPs for forestry operations generally and forest roads in particular. It is clear that forestry practices have changed dramatically over the past several decades and that BMPs are effective in minimizing water quality impacts. Paired watershed studies have demonstrated that implementing a suite of contemporary BMPs reduces sediment loads to streams by 80% or more relative to uncontrolled forestry operations. With contemporary BMPs, effects of forestry operations on water quality are generally small compared to effects of natural disturbance and annual weather cycles. Specific BMPs for roads have been tested in controlled studies and proven effective by road inventories conducted by forestry agencies in several states. Those inventories show that road BMPs are being implemented at high rates and are effective in reducing risks to water quality; road drainage structures are being disconnected from streams; poor road/stream crossings are being identified and corrected; and landslides from forest roads are being reduced.

KEYWORDS

best management practice (BMP), nonpoint source (NPS), roads, silviculture, sediment, temperature, turbidity, water quality

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 988 (July 2011). *Comparison of road surface erosion models with measured road surface erosion rates.*

Technical Bulletin No. 966 (September 2009). *Compendium of forestry best management practices for controlling nonpoint source pollution in North America.*

Technical Bulletin No. 483 (February 1986). *A study of the effectiveness of sediment traps for the collection of sediment from small forest plot studies.*

Canadian watershed handbook of control and mitigation measures for silvicultural operations (April 2009).
http://www.ncasi.org/programs/areas/forestry/canadian_program/watershed_mgmt/handbook.aspx

Forest roads and aquatic ecosystems: A review of causes, effects, and management practices (A white paper prepared by the NCASI Forest Watershed Task Group) (September 2003).
http://www.ncasi.org/Publications/Detail.aspx?id=2610

ÉVALUATION DE L'EFFICACITÉ DES MEILLEURES PRATIQUES D'AMÉNAGEMENT FORESTIER (MPAF) MODERNES : LES CHEMINS FORESTIERS

RAPPORT SPÉCIAL N° 12-01
JANVIER 2012

RÉSUMÉ

Les effets de l'aménagement forestier sur les ressources en eau font l'objet de travaux de recherche depuis longtemps. Les résultats de ces travaux ont donné lieu au développement et à l'amélioration continue des meilleures pratiques d'aménagement forestier (MPAF) pour limiter les effets des activités forestières sur la qualité de l'eau et les utilisations bénéfiques. Le présent rapport est une synthèse des travaux de recherche qui ont été réalisés sur l'efficacité des MPAF en général et, plus particulièrement, l'efficacité de celles qui s'appliquent aux chemins forestiers. Il est clair que les pratiques forestières ont considérablement changé au cours des décennies et que les MPAF sont efficaces pour réduire l'impact de ces pratiques sur la qualité de l'eau. Des études sur des bassins versants appariés ont montré que l'implantation d'un ensemble de MPAF modernes réduisait la charge en sédiments dans les cours d'eau de 80% et plus par rapport à la charge associée aux activités forestières sans mesures de contrôle. Lorsqu'on adopte les MPAF modernes, les effets des activités forestières sur la qualité de l'eau sont généralement faibles comparativement aux effets des perturbations naturelles et des cycles climatiques annuels. Dans un certain nombre d'études contrôlées, on a testé des MPAF s'appliquant spécifiquement aux chemins forestiers et, grâce à des inventaires routiers réalisés par des organismes forestiers dans plusieurs États américains, on a constaté qu'elles étaient efficaces. Ces inventaires montrent que les MPAF qui s'appliquent aux chemins forestiers sont largement adoptées et sont efficaces pour réduire les risques de détérioration de la qualité de l'eau. On ne relie plus les structures de drainage des chemins à un cours d'eau, on identifie et on corrige les ouvrages de franchissement des cours d'eau en mauvais état et on met en place des mesures pour réduire les possibilités de glissements de terrain causés par les chemins forestiers.

MOTS-CLÉS

chemins, meilleure pratique d'aménagement forestier (MPAF), qualité de l'eau, sédiment, source diffuse, sylviculture, température, turbidité

AUTRES PUBLICATIONS DE NCASI DANS CE DOMAINE

Bulletin technique n° 988 (juillet 2011). *Comparison of road surface erosion models with measured road surface erosion rates.*

Bulletin technique n° 966 (septembre 2009). *Compendium of forestry best management practices for controlling nonpoint source pollution in North America.*

Bulletin technique n° 483 (février 1986). *A study of the effectiveness of sediment traps for the collection of sediment from small forest plot studies.*

Canadian watershed handbook of control and mitigation measures for silvicultural operations (avril 2009). http://www.ncasi.org/programs/areas/forestry/canadian_program/watershed_mgmt/handbook.aspx

Forest roads and aquatic ecosystems: A review of causes, effects, and management practices (un livre blanc rédigé par le Groupe de travail sur les bassins versants forestiers de NCASI) (septembre 2003). http://www.ncasi.org/Publications/Detail.aspx?id=2610

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ASSESSING THE EFFECTIVENESS OF CONTEMPORARY FORESTRY BEST MANAGEMENT PRACTICES (BMPs): FOCUS ON ROADS

1.0 INTRODUCTION

The forest community has a long history of research designed to assess the impacts of forest practices on water quality and beneficial uses. Roads have been identified as potentially important sources of sediment in forested watersheds. This report describes watershed research to assess the effectiveness of best management practices (BMPs), focusing on forest roads.

Over more than a century of forest watershed research (e.g., Bates and Henry 1928) there have been hundreds of studies to measure the impacts of forest management on water quality and quantity and to develop control practices (Ziemer and Ryan 2000; Ice and Stednick 2004a, 2004b). It is reasonable to ask why there are so many ongoing studies of forestry BMP effectiveness. Any real-world test designed to evaluate the effectiveness of some forest practice faces many variables. On what type of soil and geology did the test occur? What were the weather conditions during the test? Was there an upstream control or paired watershed to assess normal variations in watershed response, and how confident are predictions of responses in the treatment watershed if there had been no treatment? Were the management practices applied realistically? How do management practices differ in this particular state or province from other areas?

Of course, the effectiveness of contemporary forest practices does not depend on any single practice, but rather on a combination of practices and nonpoint source control program elements that are designed to complement each other and provide redundancy for resource protection. For example, the first step in controlling sediment losses from a road is determining where the road should be located to meet management objectives. Because management operates with an existing infrastructure of roads, the decision is often between moving the road or working with the road system already in place.

Management systems for forest roads include erosion control practices that are applied on cut slopes, fill slopes, and running surfaces, as well as drainage structures designed to disperse flow from the road prism. For example, research has shown that surfacing roads with rock or even establishing a grass cover on temporary roads can reduce sediment losses. There may be a zone below the road designed to settle out sediment, and windrowing of slash can be used to further enhance sediment trapping. Because each watershed, treatment, and site is different, not only are appropriate individual practices different but the combinations of practices that can be applied are different.

Some argue that models are needed so that the variability inherent in watershed studies can be addressed through multiple simulations, but there are often unexpected consequences that models would not predict. For example, removing trees adjacent to non-fish bearing reaches might have been modeled in a way that predicted large temperature increases, but work at the Hinkle Creek Watershed Study and the Alsea Watershed Study Revisited, both in Oregon, finds small increases or even decreases in temperature for some types of harvests. Closer inspection of the physics of these sites indicates that shade from riparian brush and slash provides substantial cover from direct solar radiation and that reduced evapotranspiration may increase stream discharge and reduce observed streamwater temperatures. Models and watershed studies work together. The studies provide experience and data for designing and calibrating models, then for validating their performance under specific conditions. The models help extend watershed lessons to a wider combination of conditions and force users to describe watershed processes numerically.

Ultimately, researchers need to look at how to make information from these case studies transferable to a general understanding of forest hydrology and the effectiveness of contemporary practices. During a recent effort in Minnesota to synthesize literature on the effectiveness of riparian management zones to protect water quality, most of the information came from outside that state (e.g., http://www.frc.state.mn.us/documents/council/MFRC_RSTC_Report_2007-08-20_Report.pdf). Still, in order to provide guidance to policy makers, it was necessary to utilize the best information that was available. The primary task was to distill key principles that can be used to evaluate the likely effectiveness of alternative practices.

This report provides an introduction to the many watershed studies that have tested forest BMPs. Its focus is on studies that provide insight into the effectiveness of contemporary BMPs for forest roads. A series of BMP effectiveness research maps is presented for three regions of the United States. As a set, these maps were first developed and presented for a special session on forestry BMP effectiveness held as part of the 2007 Society of American Foresters National Convention. Next, experience from state BMP implementation and effectiveness surveys is summarized. Finally, a summary of the effectiveness of individual road practices is provided. In total, these lines of evidence provide a measure of the effectiveness of contemporary forestry BMPs in general and of forest road BMPs in particular.

While there are many challenges to understanding the combined lessons of this research and monitoring, foresters must continue to look at ways to translate and extend their findings. The final sentence of *A Century of Forest and Wildland Watershed Lessons* (Ice and Stednick 2004a) sums up the challenge.

> "Ultimately watershed studies are warranted only if the information they provide allows forest and wildland managers to make a real difference in their impacts on water quantity, water quality, and beneficial uses of water."

Based on comparisons between contemporary and historic forest management practices, the information these forest watershed studies are providing is making a difference.

2.0 THE SOUTH

Figure 1 shows a synthesis of research on forest BMP effectiveness conducted in the South. Appendix A provides references and links to the sites identified.

An early synthesis of research on forest roads and potential BMPs summarized that "up to 90 percent of sediment from timbering activities comes from temporary and permanent roads" (Yoho 1980, p. 31). Some of the first studies on erosion from forest roads and how to minimize sediment in streams were conducted at the Coweeta Hydrologic Laboratory near Otto, North Carolina. Riedel et al. (2007) provided an excellent summary of forest road research there. They reported that as early as 1935, scientists at Coweeta were finding significant reductions in soil losses from forest roads with mulching or vegetating cut and fill slopes.

> "The impacts of forest harvesting on sediment yield are directly related to skid trail layout and road building and maintenance activities associated with gaining forest access and removing timber from the woods. When roads and skid trails associated with forest harvesting are properly constructed and maintained, forest harvesting generally has a minimal impact on stream sedimentation. Conversely, poor logging practice and the incorrect design and maintenance of forest roads cause significant stream sedimentation. Many historical and often ill-conceived methods of forest road construction and maintenance caused large increases in forest soil erosion and stream sedimentation. Based on decades of research to improve road construction and maintenance, numerous practices that minimize erosion and sedimentation have been identified. Examples of these practices are coarser paving gravels, grassed roadbeds, the construction of broad based dips, brush sediment barriers along road margins and road buffer strips.

Sedimentation of streambeds may also be prevented by the proper use and maintenance of forest road BMPs. Indeed, in steep mountain streams, forest road construction and adoption of BMPs may facilitate stream restoration because the reduction of road sediment yield allows streams to flush themselves of previously deposited road sand and fine gravel" (p. 203).

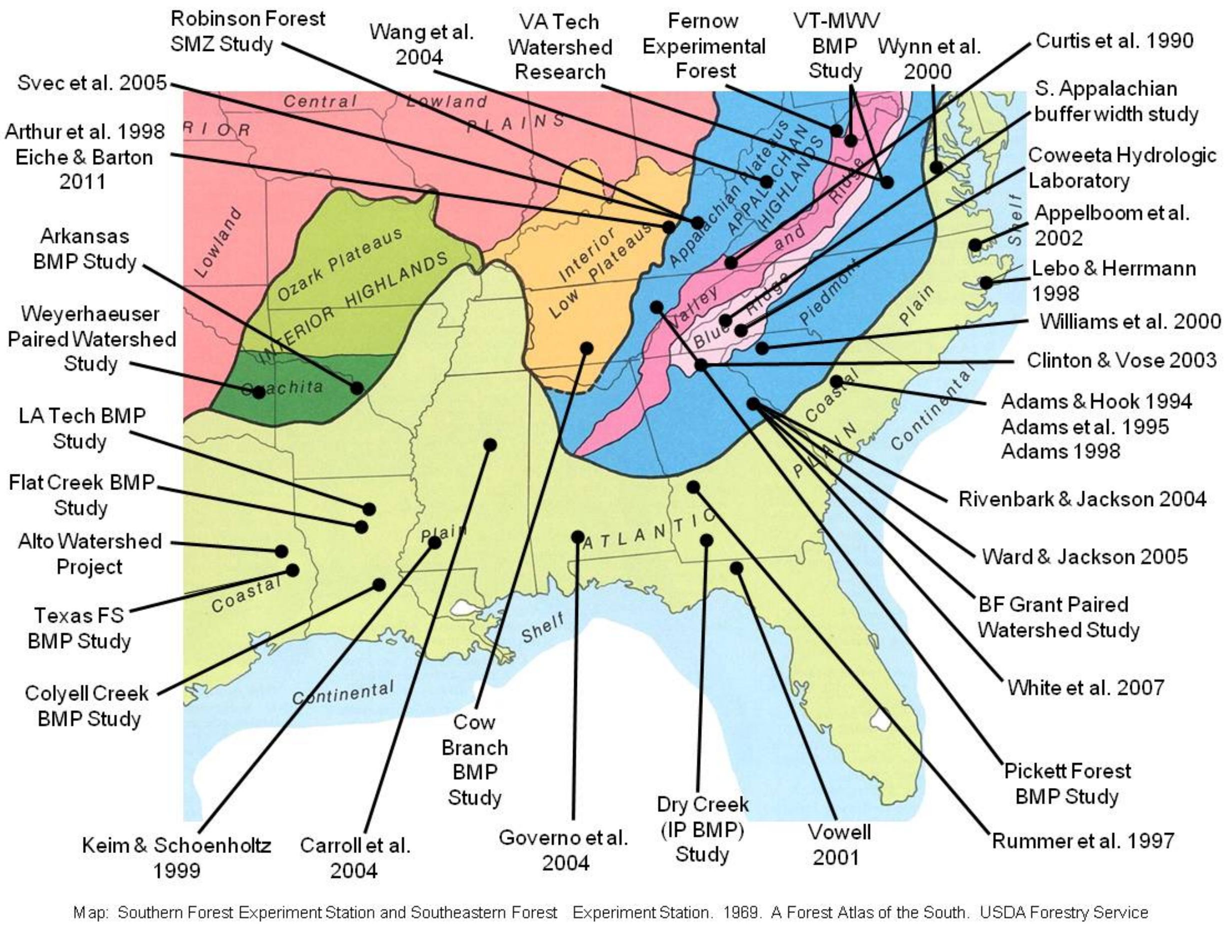


Figure 1 Map of Forestry BMP Effectiveness Studies in the Southeastern United States [SOURCE: Dr. Masato Miwa, formerly with International Paper Company]

Work on forest roads has continued. Riedel and Vose (2003) reported on a collaborative research effort in the Conasauga River of northern Georgia to optimize forest road BMPs using models that prioritized road segments for reconstruction. They reported that long-term erosion from roads appeared to be reduced by 70% after reconstruction with BMPs despite a 46% increase in average storm size (area depth per storm).

Jackson et al. (2004) provided another excellent summary of forest watershed research in the South. In addition to work at the Coweeta Hydrological Laboratory, they summarized research at Fernow Experimental Forest in West Virginia, the Oxford Hydrological Laboratory in Mississippi, the Grant Forest in Georgia, the Intensive Management Practices Assessment Center in Florida, the Santee Watershed in South Carolina, the Belle Baruch Hydrological Institute in South Carolina, the Mobile-Tensaw River Delta Study in Alabama, and the Coastal Plains of North Carolina. They provided a table showing research results from Coweeta and Fernow on key road-related issues including soil loss from ineptly located and managed logging roads, soil loss from well-located forest roads, distances soil carries across the forest floor, and principles of forest road design to minimize soil erosion. Key findings were:

- The greatest potential for increases in sediment from forest activities is associated with poorly designed and maintained roads and channel disturbance for hilly and mountainous sites. Practices that reduce these impacts can greatly reduce overall changes in sediment related to forest activities.
- Roads may not be an important source of sediment for flat sites.

A number of forest road studies have been conducted in the mid-South. Vowell (1985) measured erosion rates and water quality impacts from recently established forest roads in Oklahoma's Ouachita Mountains. He reported:

> "Ephemeral streams adjacent to the road were sampled to determine if water quality was being influenced by road runoff. Water quality data confirmed that some sediment delivery from the road was occurring. However, maximum and mean levels of turbidity and total suspended solids were greater at sampling points above than at points below road runoff input. The relative insignificance of road sediment delivery was attributed to dilution" (p. 152).

Vowell found that upslope contributing area was a key factor in erosion rates observed, so ridge roads benefit from both lower erosion rates and greater opportunities for sediment to settle out before it reaches a stream channel.

Miller, Beasley, and Covert (1985) reported on forest road studies in Arkansas. Sediment delivery to streams was estimated based on road gradient and whether road runoff was to the forest floor or directly to a stream. They estimated that about 10% of road erosion was delivered to the stream network.

Turton, Smolen, and Stebler (2009) found that unpaved rural roads in the Stillwater Creek Watershed in Oklahoma yielded significant amounts of sediment directly to streams. Sediment yields across unimproved road segments averaged 138 Mg ha^{-1} yr^{-1} (area basis) or 120 Mg km^{-1} yr^{-1} (road length basis). Installation of BMPs (proper crowning for drainage, geotextile fabric, gravel) reduced sedimentation rates by as much as 80%.

Two recent studies in the Virginia Piedmont evaluated the effectiveness of seeding, mulching, and slash applications to skid trails on harvested sites in steep terrain. Wade et al. (in press) found that water bars coupled with seeding reduced sediment rates from bladed skid trails in the Appalachian Piedmont by 77%. Bladed trails with water bars and either hardwood slash, pine slash, or mulch reduced sediment erosion rates by 93.5, 95.7, and 97.8%, respectively. In a similar study, Sawyers et al. (in press) evaluated erosion control effectiveness and implementation costs of five similar BMPs for overland skid trail closure. Findings indicated that seeding alone was the least expensive BMP (beyond water bars alone), but it was only moderately effective at limiting erosion. Incorporating slash onto overland skid trails during harvesting activities appeared to be the best option for reducing BMP costs while ensuring long-term soil stability on soils associated with log skidding.

Two key studies provided a scale of sediment impacts from road practices and other forest management activities for historic and contemporary forestry in the South: the Grant Forest Study in Georgia and the Alto Watershed Study in East Texas.

Hewlett (1979) conducted a paired watershed study at the University of Georgia's Grant Forest, with one watershed serving as a control and the other logged with methods consistent with the practices of the day. Hewlett observed that sediment losses were low compared to other land use activities when viewed over a full harvest rotation, but he also noted that sediment losses could have been reduced tenfold with just three management changes: better road design, location, and maintenance; wider buffers; and avoiding machine planting that mechanically disturbed historic cotton-era gullies. Research by Williams et al. (2000) on another set of Piedmont watersheds substantiated this assessment, with observed sediment losses about 10% of those observed by Hewlett the first years after harvesting. Another study at the same watershed examined by Hewlett confirmed the observations by Williams et al., but also found that most of the sediment from a recent harvest came from the stream channel, not from the road (Dr. Rhett Jackson, University of Georgia, pers. comm.). This body of work shows how effective BMPs have been in reducing water quality impacts, and that roads may no longer be the major sediment sources following harvests.

At the Alto Watersheds in East Texas, McBroom et al. (2008) conducted a replicated paired watershed study with BMPs applied on the same watersheds studied by Blackburn, Wood, and De Haven (1986) more than 20 years earlier. In the original study, treatment watersheds were harvested without streamside management zones and prepared for tree planting by shearing and windrowing vegetation that remained after harvest. In the more recent study, streams were protected by streamside management zones and soil disturbance was minimized by preparing harvested areas for replanting by using herbicides to control competing vegetation. Sediment loss following harvest and site preparation was 80% less in the recent study than in the original study.

McBroom (2011) reported on efforts to measure road erosion rates and contributions of roads to stream sediment loads in the Alto Watersheds. Road erosion rates generally increased with slope and traffic. In two of the large watersheds in the study, road culverts and turnouts were not connected to streams and it was estimated that roads had no effect on stream sediment loads. The other two watersheds each had two direct-delivery road segments. The portion of total stream sediment load attributed to roads was 15% in one watershed and 70% in the other. However, these estimates of sediment losses from roads were calculated using a model (SEDMODL2). Efforts to validate the model at Alto indicated that actual sediment losses from roads were lower than predicted by the model.

Southern states have taken an innovate approach to assessing BMP effectiveness through state assessments of significant risks to water quality. In 2007, under guidance from the Southern Group of State Foresters (SGSF), states instituted field evaluations of significant risks to address a common question: How should risks to water quality resulting from failures to implement or properly implement BMPs be evaluated and documented? The SGSF's Water Resources Committee determined that documenting significant risks was important for three reasons:

> "First, risk assessment lends much credibility and integrity to the BMP monitoring process by recognizing that high risk conditions can occur, and that prevention and/or restoration is a high priority for state forestry agencies. Second, routine documentation of significant risk will determine whether such instances are the exception rather than the rule, and that lack of BMPs during a silviculture operation may not necessarily equate to or result in a water quality problem - this is particularly important as it relates to BMP effectiveness monitoring. Finally, providing forest landowners with an objective risk assessment is a valuable public service that not only protects the environment, but can also protect the landowner and/or operator from what might otherwise result in enforcement proceedings or other personal liability" (SGSF 2007, p. 9).

In general, the number of water quality risks is small and states note declines in significant risk observations. For example, Florida reported only two instances of significant risk in its 2009 implementation report (FDOF 2010). In Georgia, the number of observed water quality risks decreased from 154 in a 2007 survey to 22 in a 2009 survey (GFC 2010). The 2009 survey averaged 0.1 risks per site compared to 0.41 risks per site in the 2007 survey, a 75.6% decrease. Significant risk data suggest that failure to implement BMPs correctly, or to implement them at all, often does not result in water quality impacts because multiple layers of BMP prescriptions in areas of high risk provide effective protections to water quality.

3.0 THE NORTH

There is a rich history of forest watershed research in the northern states. Figure 2 shows locations of field studies on forest BMP effectiveness in the region. Appendix B provides information about website links and references for these investigations.

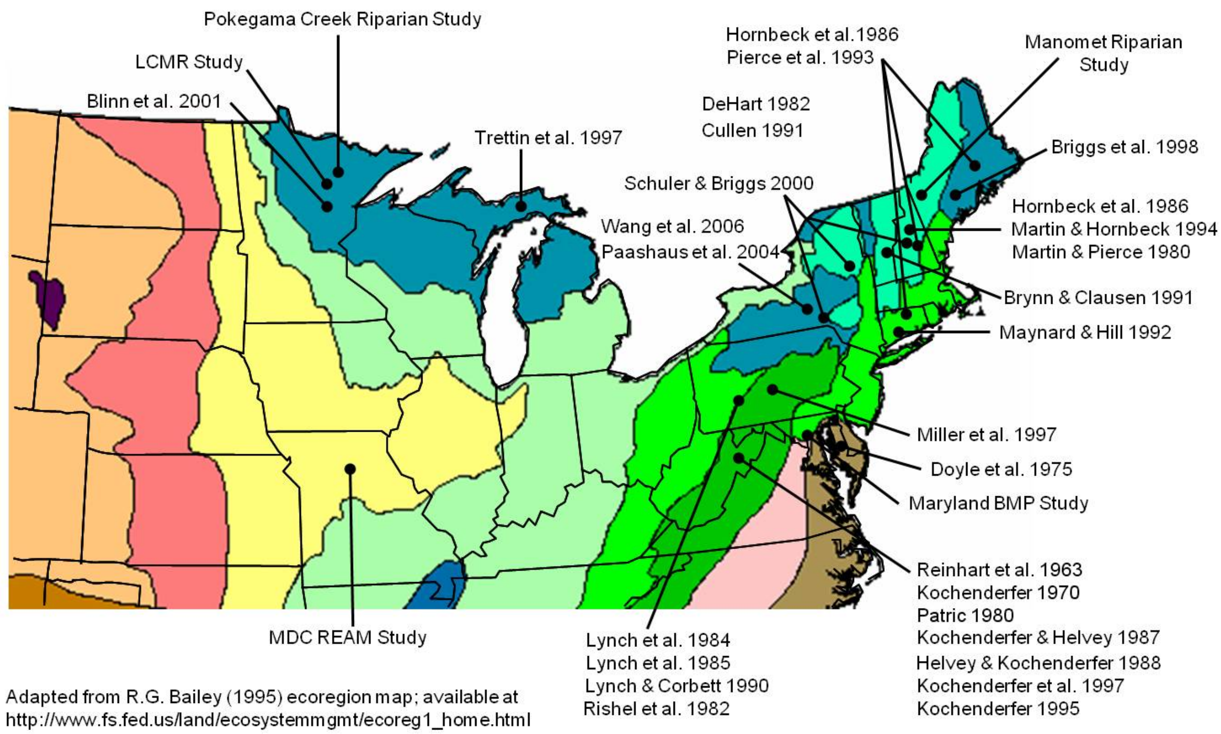


Figure 2 Map of Forestry BMP Effectiveness Studies in the Northern United States [SOURCE: Dr. Erik Schilling, NCASI]

One of the first watershed studies in the United States was initiated in 1911 and 1912 at Hubbard Brook, New Hampshire (Hornbeck and Kochenderfer 2004). Studies at Hubbard Brook and other watershed research sites in the North are best known for measuring effects of forest disturbance and acidic deposition on forest nutrient cycles. Contributions of these studies to understanding of forestry BMPs are also significant. In their reviewing these contributions, Hornbeck and Kochenderfer stated:

> "A general consensus is that terrestrial and aquatic ecosystems in the Northeast can be protected by following known precautions and guidelines for constructing and maintaining roads and skid trails" (p. 25).

> Verry (2004) observed that “fine sediments (sand and silt) also can be introduced to streams where gravel and native material roads cross them. This sedimentation is enough in smaller (<10 m wide) streams to fill pools and cover riffles” (p. 150). Verry also noted that “fine sand from roads can be stopped by diverting road ditch runoff onto the floodplain and by surfacing the road at the crossing with crush rock (or blacktop)” (p. 147).

Researchers in West Virginia at the Fernow Experimental Forest and elsewhere have conducted several important studies of forestry BMPs.

- Reinhart, Eschner, and Trimble (1963) conducted a pioneering study of the effectiveness of control practices to reduce water quality impacts from forest management activities. It involved four treated watersheds and a control. Maximum stream turbidity was 56,000 ppm in two watersheds managed without erosion control measures. In contrast, turbidity was 15 ppm for the control and 25 ppm for a carefully managed watershed.
- Kochenderfer and colleagues produced a series of important reports based on their BMP research (see Appendix B) including an early “how to” guide for controlling erosion from forest roads (Kochenderfer 1970).
- Patric (1980) evaluated effects of silvicultural treatments on streamflow over a 20-year period on a 34.7 ha forested catchment. Selection harvest of 13, 8, and 6% of the basal area in 1958, 1963, and 1968, respectively, had negligible effects on any measured properties of water. In 1969 to 1970, 31.7 ha were harvested by clearcutting, leaving a 3.0 ha protective strip of lightly cut forest extending about 20 m along both sides of the stream channel. This harvest had no effect on stormflow or stream temperature. Concentrations of sediment, nitrate, calcium, magnesium, potassium, and sodium in streamflow increased slightly. These effects on water quality were held to low levels by the protective strip and prudent management of logging roads.
- Helvey and Kochenderfer (1988) identified culvert sizes needed to pass flows in the central Appalachians.
- Wang, McNeel, and Milauskas (2004) **s**ummarized the history of West Virginia’s forestry BMPs following the state’s adoption of the Logging and Sediment Control Act.

Research on BMP effectiveness at the Leading Ridge Watershed in Pennsylvania was summarized by Lynch and Corbett (1990).

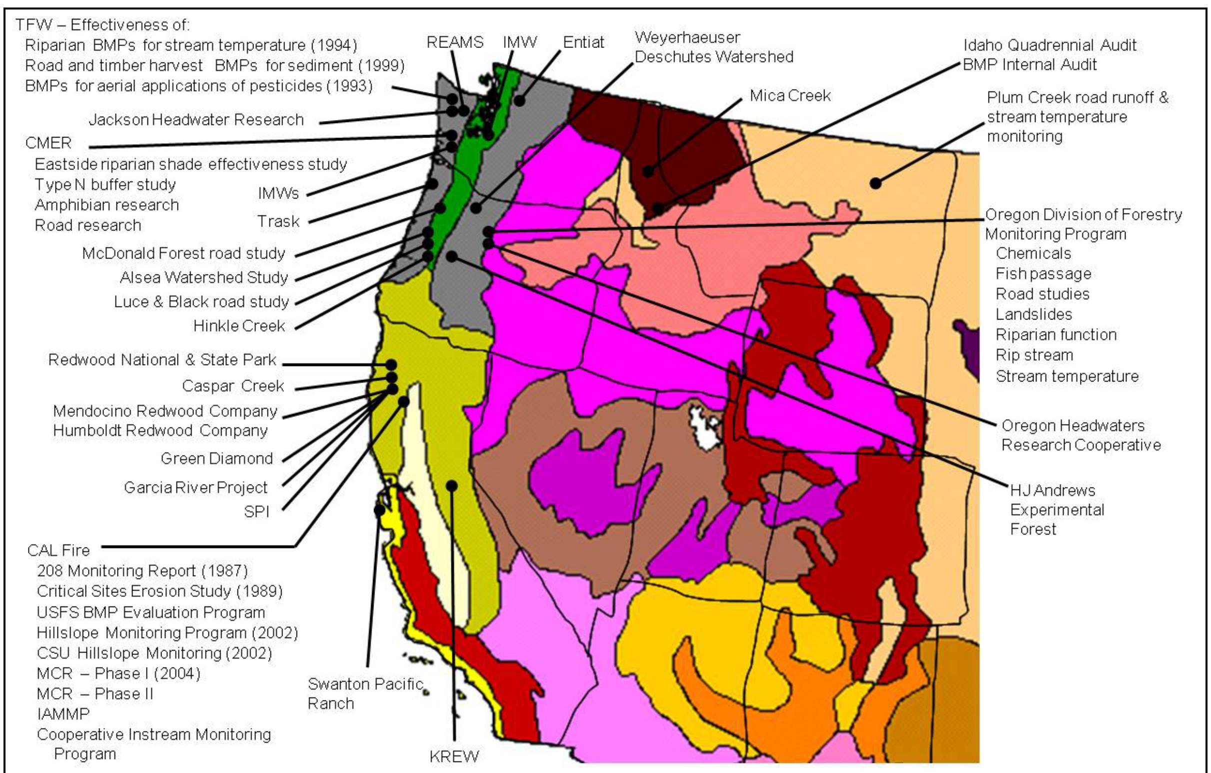
> “Fifteen years of streamflow and water quality data were evaluated to determine the effectiveness of Best Management Practices (BMP’s) in controlling nonpoint source pollution from a 110 acre commercial clearcut located in the Ridge and Valley Province of central Pennsylvania. The analyses addressed both short- and long-term changes in the physical and chemical properties and the hydrologic regime of the stream draining this 257-acre watershed. Overall, the BMP’s employed on this commercial clearcut were very effective in preventing serious deterioration of stream quality as a result of forest harvesting. Although statistically significant increases in nitrate and potassium concentrations and temperature and turbidity levels were measured the first two years following harvesting, the increases were relatively small and, with the exception of turbidity, within drinking water standards. Nevertheless, such increases may violate EPA’s anti-degradation policy. Nitrate and potassium concentrations and turbidity levels remained above pre-harvesting levels for as long as nine years following harvesting” (p. 41).

4.0 THE WEST

Figure 3 is a map of research sites addressing forest BMP effectiveness in the West. Appendix C provides information about website links and references for the research shown in the figure. Forest roads in the West are often challenged by combinations of steep terrain and sensitive fish communities. Concerns include surface erosion, gully and rill erosion, and mass wasting (landslides). Research in the West has identified some key principles of forest road sediment impacts. Of course, these principles generally apply elsewhere as well.

Most erosion comes from a small fraction of the road network. A common saying among forest hydrologists is that 20% of the road network contributes 80% of the sediment. For example, Rice and Lewis (1991) found that critical road sites with erosion features greater than 100 yd^3 ac^{-1} represented just 2% of the roads network but 70% or more of the erosion measured. Similarly, Cafferata, Coe, and Harris (2007) reported that only 5.5% of drainage structures in California had sediment-related problems. By inventorying for these "problem" segments and applying appropriate BMPs, road managers can greatly reduce overall road impacts to the watershed.

With forest roads, as with real estate, it's all about location. For a given watershed, certain portions of the landscape are more prone to erosion or sediment delivery to streams than others. Inner gorge locations or mid-slope roads may be subject to increased landslides (Furbish and Rice 1983). Roads located adjacent to streams may have high rates of sediment delivery without opportunities to settle sediments before they enter streams. Forest managers continually balance the environmental costs and benefits of building new roads or using existing roads in sensitive locations.



Adapted from R.G. Bailey (1995) ecoregion map; available at http://www.fs.fed.us/land/ecosysmgmt/ecoreg1_home.html

Figure 3. Map of Forestry BMP Effectiveness Studies in the Western United States [SOURCE: Dr. George Ice, NCASI]

The shape and surface of a road influences its ability to handle traffic and its erodibility. Roads without adequate drainage may be unable to shed water, resulting in rutting and road breakdown. Toman and Skaugset (2007) found that sediment losses from road surfaces are greatest where ruts form, providing a physical indicator of the sediment source. Coe (2006) found a 16-fold difference in sediment generation between rocked and un-rocked roads.

Seeding, mulching, and applying slash can reduce erosion from exposed cut slopes and fill slopes and from the road surface. Megahan (1978) found that planting trees and mulching reduced erosion from road fills by 44% and 95%. In Idaho, McGreer (1981) demonstrated the effectiveness of piled slash in reducing soil erosion from skid trails by 99%.

Dispersing flow off roads and detaining it once it leaves the road prism allow increased settling of sediment to the forest floor before it reaches a stream. Effective spacing of water control structures (rolling dips, relief culverts, belt diverters, etc.) as gradients steepen and along lower topographic road segments as well as utilizing high quality gravel on the road bed reduce sedimentation (Packer 1967; Mills, Dent, and Robben 2003). Travel distances for sediment transport below roads can be used to locate roads far enough away from streams to allow for settling (Brake, Molnau, and King 1997).

Direct delivery from hydrologically connected roads can be a major source of fine sediment to streams (Bilby, Sullivan, and Duncan 1989; Ketcheson and Megahan 1996; Furniss, Flanagan, and McFadin 2000; Mills, Dent, and Cornell 2007). The forestry community is actively disconnecting legacy roads and constructing new roads to avoid these conditions. Martin (2009) reported on a survey of 1047 miles of private forest roads in eastern and western Washington. He found that 73% of the road network had low delivery potential (located on ridgelines, in shallow terrain, or without crossing defined channels). About half of the road system with high delivery potential was disconnected. Based on that survey, about 12% of the road network was hydrologically connected. Mills, Dent, and Cornell (2007) documented reductions in the amount of the road network delivering directly to streams. It would be impossible to remove all direct delivery culverts and ditches, but the forest community is making progress and has other BMPs, such as special hardening of sensitive road segments, that reduce sediment impacts.

Landslides and gullies formed by flow diversion from roads and crossings can be major sediment sources in steep terrain. Early landslide inventories indicated that most mass wasting events occurred on roads built with sidecast construction methods on steep slopes and other inappropriate practices (NCASI 1985). Today, forest practices have changed and these problems are being addressed by storm-proofing roads and upgrading culverts and stream crossings to avoid catastrophic failures (Cafferata, Coe, and Harris 2007). Recent surveys indicate that road-associated landslides make up a small percentage of the total number of slope failures (Robison et al. 1999). Catastrophic flow diversion down roads can be avoided by sloping both road approaches (short road segments) toward the stream (Hagans and Weaver 1987).

Road maintenance is a balancing act between using sufficient treatment to keep the road safe and minimizing berms, rutting, and too much disturbance. Reducing the frequency of grading can significantly reduce sediment yields from roads (Sugden and Woods 2007).

Legacy road conditions, rather than current activities, are often sources of sediment impacts. The forestry community is conducting road inventories, upgrading roads, and decommissioning roads to address legacy issues (Sullivan 2003; Cafferata, Coe, and Harris 2007). Active forest management creates opportunities to upgrade roads (Ziesak 2009; Elliot 2010).

One overall lesson from forest BMP research is that how forestry is practiced is as important as how much, where, and when those practices occur. Forest road BMPs should recognize and avoid high erosion hazard areas or provide special practices where high hazard areas are unavoidable. For example, Bourgeois (1978) found that road failures (landslides) actually occurred less frequently from steep hill slopes than from moderate slopes, presumably due to extra precautions in road construction practices on the higher risk sites. Planning can minimize the total amount of landscape disturbed by roads, both miles of road and the road footprint (fill slope, cut slope, road prism). Roads should be engineered to have stable surfaces and stream crossing structures that impose minimum impacts. Practices to achieve these goals include designing drainage features and stream crossings to reduce erosion, reducing bare ground and soil compaction, separating bare ground from surface waters, and minimizing delivery of road-derived sediments. In addition, stream crossings should allow for passage of fish, other aquatic biota, large wood, and sediment. Riparian management areas should be retained around streams. As much as possible, road networks should be kept out of riparian areas and the number of permanent and temporary road crossings should be minimized. Roads and stream crossings should incorporate designs that anticipate triggering events (e.g., high rainfall events, hurricanes, tropical storms) so that small failures do not cascade into major events. Periodic monitoring is essential to keep BMPs operating and identify emerging road sediment issues.

A number of important studies in the West have delved into road contributions to sediment budgets for forest watersheds. Three early studies of forest management impacts on water quality were the Alsea Watershed Study in coastal Oregon; the H.J. Andrews Watersheds 1 to 3 in the Oregon Cascades; and Caspar Creek in coastal northern California.

The original Alsea Watershed Study (1959 to 1973) assessed the effects of timber harvesting on water, aquatic habitat, and salmonid resources using a paired watershed approach (Stednick 2006). That study was a catalyst for adoption of the Oregon Forest Practices Act (OFPA) and strongly influenced the original OFPA rules. Those early findings supported the use of riparian management areas near fish-bearing streams to minimize water quality impacts, as well as careful road construction methods. Beschta (1978) and Beschta and Jackson (2006) reported on sediment responses from roads for a patch cut watershed (Deer Creek) in that study. They found that the sediment increase in Deer Creek was primarily from road failures (landslides), probably resulting from sidecast road construction.

This pattern was matched in the H.J. Andrews paired watershed studies conducted at Watersheds 1, 2, and 3. Watershed 3, which was patch cut like Deer Creek, experienced severe road failures that resulted in scour and deposition reaches in the main channel (Grant and Wolff 1991). In fact, 85% of total sediment losses for Watershed 3 observed over a 30-year period occurred during a single storm in 1964. Landslide inventories conducted for the H.J. Andrews identified sidecast road construction as a risky practice that could lead to greatly increased landslide frequency (NCASI 1985). Forest practice rules require that this road practice no longer be used, and there are even sidecast pull-back programs designed to upgrade existing roads and reduce risks of landslides from road failures.

The Caspar Creek Watershed Study involved two phases (Ziemer 1998). Monitoring began in 1962. In the first phase, the South Fork of Caspar Creek was the treated watershed and the North Fork served as a paired control. The South Fork was selectively harvested between 1971 and 1973. After recovery of the South Fork following the first harvesting phase, the watershed treatments were reversed and the North Fork was the treated watershed while the South Fork became the control. The North Fork had patch clearcuts between 1985 and 1991. Between the two study phases, the state of California adopted a Forest Practices Act and rules. The first harvest used tractor logging, and roads were built near the stream. These roads experienced numerous landslides and delivery to the stream channel (Cafferata and Spittler 1998). The second harvest followed forest practice rules, and roads were away from streams. Road erosion for the second phase was estimated to be less than half that observed in the first study and “because the roads were located away from streams, this erosion did not contribute significantly to sediment loads” (Rice, Ziemer, and Lewis 2004, p. 230). Logging-related erosion was also lower, approximately half that observed in the first study, and suspended sediment was reduced. The combination of changes in road practices and yarding/harvesting activities resulted in substantial reductions in sediment impacts compared to the earlier study. In fact, Cafferata and Spittler (1998) noted that landslides from legacy road practices in the South Fork continued to contribute sediment inputs, while this was not observed for the North Fork.

In addition to the research at Caspar Creek, many more extensive studies in northern California were designed to identify sources of sediment from forest management. These were summarized by Rice, Ziemer, and Lewis (2004). Some of the first studies tested the effectiveness of erosion hazard ratings that were supposed to help in the design of appropriate forest practices. A couple of key findings from those studies were that 1) most of the erosion observed came from a few plots (68% of erosion from less than 4% of plots) and 2) operator behavior was responsible for a large amount of the variability in erosion between plots. A study of 344 one-mile segments of Forest Service roads found that 60% of basin erosion was from roads and 95% of road-related erosion was from mass wasting. This led to additional work to identify sites with a high susceptibility to landsliding. Cafferata, Coe, and Harris (2007) provided an excellent update of lessons learned about controlling erosion from forest roads. In addition to an extensive summary of research findings about road practices, they discussed the environmental costs and benefits of road improvement efforts designed to reduce sediment impacts. For example, they noted that there can be “short-term sediment impacts due to channel adjustments following crossing removal” (p. 47). In the central Sierra Nevada, Coe (2006) found 16 times greater median sediment production for un-rocked forest roads than for rocked roads.

Some of the pioneering work on erosion from forest roads, cumulative watershed effects, and the use of BMPs to reduce water quality impacts, as well as erosion and sediment model development, was done by Dr. Walt Megahan and colleagues working in the Idaho Batholith and other locations. One example of the culmination of this work is a case study on BMPs and cumulative effects from sedimentation in the South Fork of the Salmon River, Idaho. Megahan, Potyondy, and Seyedbagheri (1992) found that intensive and poor logging practices conducted from 1940 through the mid-1960s contributed to massive cumulative sediment generation and delivery to (and deposition in) the South Fork Salmon River. This sediment negatively affected valuable salmon and steelhead habitat. Modeling showed that these impacts could have been reduced by 45 to 95% with present-day management practices that included BMPs.

A study at Mica Creek in northern Idaho was designed to test the effectiveness of the Idaho Forest Practices Act rules (Karwan, Gravelle, and Hubbart 2007). It involved a nested paired watershed study with treatment of two headwater basins (one clearcut and another partial cut) and monitoring at upstream and downstream treatment and control sites. The existing road in the headwaters was upgraded and a new road was constructed in the treatment watersheds. Road BMPs included an outsloped road design, installation of relief culverts near stream crossings (to get water off the road before it got to the stream), and creation of filter windrows along the fill slopes. The roads were improved or constructed beginning in 1997 and harvesting and yarding did not occur until 2001, allowing a period to assess the roads-only impact on sediment (although truck use during harvesting is also an important potential contributor). Karwan, Gravelle, and Hubbart concluded that

> “the impacts corresponding to road construction remain difficult to discern. The impacts corresponding to timber harvest differ based on harvest treatment and time period of analysis. Results suggest a correlation between increased sediment loads and clearcutting for a brief period following the harvest. No significant correlation was found in the partial cut watershed” (p. 181).

These extremely mild sediment responses under contemporary forest practice rules must be compared to historic impacts such as those seen at the original Alsea Watershed Study, H.J. Andrews, and the first phase of Caspar Creek. It is important to note that biological monitoring suggests little impact to the aquatic communities from these forest activities. Gravelle et al. (2009) reported that "little or no change in macroinvertebrate communities resulted from road construction and timber harvest activities in the [Mica Creek] watershed" (p. 352).

One of the most compelling stories demonstrating the effectiveness of forest BMPs in general and BMPs for forest roads in particular, is that of the Deschutes River Watershed in Washington (Reiter et al. 2009). This watershed is managed intensively for timber and has an extensive road network. Monitoring for turbidity over 30 years at sites from headwaters to the mainstem (draining a 150 km^2 watershed) found declining turbidity levels even though active forest management continues, and runoff patterns do not explain this response. "Our results suggest that increased attention to reducing sediment production from roads and minimizing the amount of road runoff reaching stream channels has been the primary cause of the declining turbidity levels observed in this study" (p. 793).

Ongoing research as part of the Watersheds Research Cooperative in Oregon is testing the effectiveness of the Oregon Forest Practices Act rules (http://watershedsresearch.org). This includes three large paired watershed studies: Hinkle Creek, the Alsea Watershed Study Revisited, and the Trask Watershed Study. Because these studies are ongoing, most results are either preliminary or are not yet published. However, forest managers are already learning much from them. Hinkle Creek, the first of the studies, showed that sediment did increase following logging in the headwaters, but fish in downstream reaches did not show a negative response. A focused study on roads has been added to Hinkle Creek. The Alsea Watershed Study Revisited has not yet found a demonstrable sediment impact in the harvested watershed, but the road system is mostly located along ridges, much like in the North Fork Caspar Creek. Like Hinkle Creek, fish populations have not shown a negative impact from the harvest or the roads. The Trask Watershed Study is still in its calibration phase, but like Hinkle Creek, it has a road monitoring component that will characterize road sediments compared to background conditions. All three paired watershed studies include both water quality and biological monitoring to assess BMP effectiveness.

5.0 FINDINGS FROM STATE BMP EFFECTIVENESS AND IMPLEMENTATION MONITORING

State silvicultural nonpoint source control programs under the federal Clean Water Act often include monitoring (in some cases repeated monitoring) to determine the effectiveness and rate of implementation of state BMPs (NCASI 2009a; Ice, Schilling, and Vowell 2010). This section highlights some key findings from these efforts.

5.1 California

Cafferata, Coe, and Harris (2007) summarized repeated efforts to identify and control sources of erosion and sedimentation from forest management activities in California. The first was a 1986 field team assessment of 100 Timber Harvest Plan sites. Poor road location, construction, and drainage and poor road abandonment practices were common reasons for adverse impacts. A follow-up study (Hillslope Monitoring Program) found that road erosion was almost always associated with improper implementation of the Forest Practices Rules (FPRs). About 5.5% of road drainage structures were not well designed, constructed, or maintained and about 15% of road erosion features delivered sediment to streams. Another monitoring project (Modified Completion Report) found that 5% of road-related features had improperly implemented rules and 8% of erosion features delivered sediment to streams. Implementation of road-related rules met or exceeded FPR requirements 82% of the time, were deemed marginally acceptable 14% of the time, and departed from requirements 4% of the time. Road practices most frequently cited for poor implementation were water break spacing and the size, number and location of drainage structures. When properly implemented, FPRs were judged to be highly effective in preventing erosion and sediment transport to streams.

5.2 Maine

The Maine Forest Service (MFS) has a long history of working closely with the state's forestry community to develop and refine forestry BMPs to protect water quality. In 2010, MFS reported results of a BMP effectiveness study using data collected from 2005 to 2009 (MFS 2010). Data in the report were collected and analyzed using the *Best Management Practices Implementation Monitoring Protocol*, an original project of the Northeastern Area Association of State Foresters' Water Resources Committee. This protocol assesses the overall effectiveness of the suite of BMPs used to maintain water quality at critical areas such as stream crossings and road approaches. The 2010 report indicates that Maine's forestry BMPs were effective at preventing sedimentation in 84% of the 500 timber harvests monitored. Sediment entering a waterbody decreased from 17% of cases in 2005 to 10% in 2009. MFS also reported that BMPs implemented by certified loggers or professional foresters were more likely to prevent sediment from entering a waterbody.

5.3 Maryland

Use of forestry BMPs is required in Maryland. In 2004 and 2005, BMPs were evaluated on 75 forest harvest sites in the state with the greatest vulnerability for pollution, particularly erosion and sediment deposition (MDNRFS 2009). The report indicated that BMPs were 77% effective in preventing sediment delivery to waterbodies on the most vulnerable harvest sites. Weighting the average to account for harvests that avoided streams, BMPs reduced sediment contributions by more than 95%. Trace amounts of sediment were reported on just 4% of monitored harvests, and measurable amounts of sediment reached waterbodies on 19% of sites. The report indicated that additional training in the areas of stream crossing installation, road and skid trail approaches, and properly installed cross drainage would significantly reduce sedimentation rates.

5.4 Minnesota

The Sustainable Forest Resources Act requires the Minnesota Department of Natural Resources to develop and administer a program, overseen and directed by the Minnesota Forest Resources Council, to monitor implementation of the Council's timber harvest/forest management guidelines on public and private forestlands. A 2008 monitoring report indicated that only 4% of forest road segments showed evidence of sediment reaching a wetland or waterbody (MDNR 2008). Skid trails delivered sediment to waterbodies in less than 1% of the segments monitored due to their location away from waterbodies, primarily outside of filter strips and riparian areas. Stream crossing approaches showed high sediment delivery (>20%), indicating that additional education and training is needed to ensure that operators use effective practices on crossings and approaches before, during, and after timber harvest.

5.5 Montana

As part of bi-annual forestry BMP monitoring, Montana asks inspectors to assess whether or not current projects include improvements to existing road systems that reduce overall sediment delivery to streams. The most recent report (Ziesak 2009) found that 50% of sites inspected showed reduced sediment delivery to streams.

5.6 Oregon

The Oregon Department of Forestry (ODF) has a long history of monitoring the effectiveness of Forest Practices Act rules, including those for roads (Monitoring Technical Reports can be found at http://www.oregon.gov/ODF/privateforests/TechReportsNumerica.shtml). Two key monitoring efforts were a study of forest road sediment and drainage for private and state lands in western Oregon (Skaugset and Allen 1998) and an inventory of landslides following a February 1996 storm (Robison et al. 1999).

Skaugset and Allen (1998) found that most roads were "in a condition where serious surface erosion was not occurring." They estimated that about 25% of the road network clearly drained to streams and another 6% might have delivered to streams. ODF has established a performance measure of 15% or less connectivity of road segments to streams. The most recent data for five watersheds in western Oregon showed that average connectivity was 15% (with a range of 8.7 to 19.8%).

Robison et al. (1999) detected 85 road-associated landslides in response to the February 1996 floods. Most were associated with road fill or sidecast failures (59 of the landslides). Road-associated landslides made up only about 10% of those inventoried, which is a much smaller fraction than found in earlier landslide inventories.

Another technical report (Mills, Dent, and Robben 2003) focused on turbidity response to wet season forest road use by monitoring turbidities above and below road crossings. Of the sites monitored, 30% showed reductions or no changes in turbidity, and 90% showed changes of less than 20 nephlometric turbidity units (NTU). The remaining 10% ranged from 20 to 520 NTU. Total precipitation greater than 1.5 to 3.0 inches over three days, the fraction of surfacing material that was silt sized or smaller, and more than 250 feet of road ditch flowing directly to the stream were factors that resulted in statistically significant increases in turbidity below road crossings. Findings from this study influenced a subsequent revision to Oregon's Forest Practices Act rules.

5.7 Washington

Several studies in Washington have been designed to assess the impacts of forest roads on water quality and to evaluate the effectiveness of the state Forest Practices Act rules. One of the first investigated suspended sediment from forest roads during road construction (Wooldridge and Larson 1980). Veldhuisen and Russell (1999) assessed forest road drainage and erosion initiation in four western Cascade watersheds as part of the Timber Fish Wildlife program: "A primary goal was to evaluate the effectiveness of regulatory approaches—Washington Forest Practices Rules and Watershed Analysis—at preventing road drainage erosion" (abstract). Changes to the Forest Practices Act rules were recommended based on the results of that study, including closer spacing between drainage structures at some sites. In response to a new requirement for road maintenance and abandonment plans, a monitoring program has recently been inventorying forest roads to document current conditions as a basis for assessing performance over time. Dubé et al. (2010) reported on the first sampling event for the 2006 to 2008 period. At least 85% of the road network inventoried was reported to meet new road standards, and an estimated 11% was found to deliver to streams or wetlands. It was estimated that 62% of sample units met the hydrologic performance targets (miles of road delivering to streams/miles of stream) and 88% met the Forest and Fish Report sediment performance target (tons of delivered sediment/year/miles of stream). Future inventories will determine whether road conditions are improving or declining.

5.8 Wisconsin

Forestry BMPs in Wisconsin are voluntary. However, there are circumstances for which compliance with BMPs is required. State forests, county forests, and private lands that have enrolled in the Managed Forest Law since 1995 must comply with the standards of the BMP program. From 1995 to 2005, Wisconsin's Department of Natural Resources (DNR) noted that when BMPs were applied correctly (where needed), no adverse impacts to water quality were found 99% of the time (WDNR 2007). When BMPs were applied, but may have been applied incorrectly, no adverse impacts to water quality were observed 98% of the time.

6.0 FINDINGS ABOUT INDIVIDUAL FOREST ROAD CONTROL AND MITIGATION PRACTICES

NCASI has developed two summaries of individual practices that can be used to moderate water quality impacts from forest operations, first for the United States and then for Canada. These control and mitigation handbooks were developed to serve as toolboxes for forest managers to help in selecting the most effective and efficient means of achieving water quality objectives. The most recent is the *Canadian Watershed Handbook of Control and Mitigation Measures for Silvicultural Operations* (NCASI 2009b). By far the largest section is on control and mitigation measures for road construction, listing 28 individual practices that can be used to reduce water quality impacts. Separate sections are provided for reducing water quality impacts as part of road operations and maintenance, and for minimizing impacts from road deactivation, removal, and rehabilitation. Several examples demonstrate current understanding of the effectiveness of individual road practices for reducing water quality impacts.

6.1 Road Location

Road location is considered to be one of the most important decisions that can be made to reduce water quality impacts. Guidelines for road location include 1) use existing roads whenever possible; 2) locate roads as far from streams as possible; 3) locate roads to follow slope contour; 4) locate roads on well drained soils and avoid wetlands, seeps, and other wet areas; 5) avoid steep, unstable slopes with a potential for landsliding; and 6) minimize the number of stream crossings. Road sediment models such as SEDMODL2 and WEPP can be used to evaluate possible delivery of sediment to streams from alternative road routes, although model performance can be poor in some cases (NCASI 2011). Furbish and Rice (1983) found that sites nearest streams and just below the change in the convex slope were most susceptible to landsliding. Madej (2001) reported that roads removed from the lower hillslope produced 50 times more sediment than roads removed from upper hillslope positions.

6.2 Timing of Road Construction near Streams

Construction can be scheduled to avoid disturbance at times when increased sediments are most detrimental to fish. For example, Noggle (1978) found that tolerance of Coho salmon to increased sediment was low in the summer and higher in the winter. The 96 hour LC_{50} for Coho was found to change 20-fold from the low in August to the high in November. Timing can also be used to avoid severe disturbance of forest roads. For example, in the Mediterranean climate of the West Coast, native-surface roads may only be used in the dry summer period to avoid the types of erosion and sediment loss that would occur with winter use.

6.3 Road Surfacing

Forest roads in erosion-prone areas can be surfaced with gravel, rock, asphalt, or other suitable materials to provide bearing strength and reduce deterioration and erosion from the road surface. Appropriate surfacing can be combined with compacting methods to further increase bearing strength and resistance to erosion. Swift (1986) found that 15 cm of crushed rock reduced sediment by 78% compared to a bare road surface. Kochenderfer and Helvey (1987) found an 87% reduction in sediment yield from roads with 15 cm of rock compared to bare soil roads. More recently, Coe (2006) found 16-fold greater median sediment production from un-rocked forest roads than from rocked roads.

6.4 Mulching, Seeding, and Stabilizing Disturbed Sites

Bare cut and fill slopes can be treated with mulch and seeding to reduce erosion rates. Burroughs and King (1989) reviewed studies from around the United States where dense grass was used for erosion control of bare soils. They found 86 to 100% reductions in sediment loss with the establishment of dense grass. On native soil roads with light traffic, Swift (1986) found 45% lower sediment yields with grass cover.

6.5 Road Drainage Structures

The spacing of cross drains is positively correlated with the length of sediment travel beneath roads (e.g., Packer 1967). Effective spacing distance decreases with steeper road gradients and with lower topographic position (ibid). The closer cross drains are spaced, the lower rill erosion (50 to 97% control reported) for the road surface will be.

6.6 Disconnecting Roads from Streams

Road drainage structures that deliver runoff directly to streams can have substantial effects on sediment loads and peak flows. In western Washington, Bilby, Sullivan, and Duncan (1989) found that 34% of road drainage structures discharged directly to streams. In the Washington Cascades, Bowling and Lettenmaier (1997) found that 45% of culverts were connected to streams directly and 57% were connected either directly or through a gully.

Companies and agencies have been disconnecting roads from streams by modifying road systems to increase the fraction of road runoff that moves over and into soil before reaching streams. Progress in these efforts was apparent in a recent survey in Washington that found only 11% of the road network was connected to streams by direct delivery culverts (Martin 2009).

Disconnecting roads from streams is effective because it allows sediment to settle and mitigates peak flows by increasing the travel time of runoff. Empirical evidence of effectiveness has been found in several field studies that have measured reductions in sediment delivery. For example, Swift (1986) studied runoff of sediment from forest roads in the Appalachians and documented effective filter strip widths based on slope and surface conditions. Ketcheson and Megahan (1996) studied sediment transport from forest roads in granitic soils and found sediment delivery decreased with increasing distance from road to stream.

6.7 Filter Windrows

Filter windrows are constructed by placing slash at the toe of fill slopes. Cook and King (1983) and Burroughs et al. (1985) found that trapped sediment increased from 15% or less to 90% or more with this practice.

6.8 Synthesis

The examples above show that individual BMPs for forest roads are effective in minimizing water quality impacts to nearby streams. More details on these and other practices are available. The *Canadian Watershed Handbook of Control and Mitigation Measures for Silvicultural Operations* (NCASI 2009b) includes not only descriptions of control practices and estimates of their effectiveness, but also information about their costs, limiting and complicating factors, complementary practices that can increase their effectiveness, and references to original literature.

7.0 DISCUSSION AND SUMMARY OF FINDINGS

In total, the results reported herein show that forestry practices have changed dramatically over the past several decades and that BMPs can be highly effective in minimizing water quality impacts. In some cases, legacy road conditions such as poor locations along streams challenge the ability of land managers to improve road performance. Nevertheless, inventories of road conditions show that the forestry community is addressing identified problems. Those inventories show that direct delivery road segments are being disconnected from streams; poor road/stream crossings are being identified and corrected; and landslides from forest roads are being reduced.

In the few cases where there have been opportunities to compare water quality impacts from past and contemporary practices, reductions in sediment loads of 80% or more have been attributed to today's BMPs. There is evidence in some of these cases that increases in sediment following contemporary harvesting are not from the road network but from in-channel scouring, perhaps due to increased stream power as a result of reduced evapotranspiration. What is clear is that these changes in water quality are often small compared to the variability seen in response to natural disturbance and annual weather cycles.

The effectiveness of road BMP packages is enhanced by redundant measures to prevent sediment delivery to streams. For example, some BMPs reduce erosion of sediment from road surfaces while others control sediment movement in runoff as it moves away from the road.

Sediment delivery from roads to streams varies greatly depending on factors such as slope, soil type, surface roughness and precipitation (form and frequency). Most road segments are not significant sources of sediment because they are located and designed in ways that prevent delivery.

The forestry community is implementing BMPs in all regions of the United States to control erosion and sediment movement from the subset of road segments that has greatest potential to deliver sediment to streams. In the few states that have identified forest roads as important sources of sediment (e.g., California), BMP implementation is mandatory and occurring in context of regulatory forest practice programs.

Despite this progress, some stakeholders remain skeptical about the effectiveness of silvicultural nonpoint source control programs that employ BMPs under either regulatory or non-regulatory programs. It will continue to be important to provide information about the effectiveness of individual BMPs, the effectiveness of BMP packages applied at a watershed scale, and the level of implementation to address lingering concerns. The forestry community has conducted literally hundreds of research and monitoring efforts to refine BMPs and to test their effectiveness. The resulting database provides a crucial toolbox for land managers and agencies to practically address water quality concerns related to forest roads.

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APPENDIX A

KEY SOURCES OF INFORMATION ON FORESTRY BEST MANAGEMENT PRACTICES EFFECTIVENESS RESEARCH IN THE SOUTH

This appendix provides references, website addresses, and other information for key research on forest best management practice (BMP) effectiveness conducted in the southern United States. For key summaries and syntheses on this subject, see Anderson and Lockaby (2011); Blackmon (1995); and papers in Ice and Stednick (2004) by Jackson et al. and Beasley et al.

Anderson, C.J., and Lockaby, B.G. 2011. The effectiveness of forestry best management practices for sediment control in the southeastern United States: A literature review. *Southern Journal of Applied Forestry* 35(4):170-177.

Blackmon, B.G. (ed.). 1985. *Proceedings of Forestry and Water Quality: A mid-South symposium.* Monticello, AR: University of Arkansas, Cooperative Extension Service.

Ice, G.G., and Stednick, J.D. (eds.) 2004. *A century of forest and wildland watershed lessons*. Bethesda, MD: Society of American Foresters.

ALABAMA

Lockaby et al. 2004: This study looked at functions provided by streamside management zones (SMZs) for three treatments: no harvest; clearcut; and partial harvest (50% basal area removal). The results suggested that both no harvest and partial harvest maintained carbon inputs to the stream compared to clearcutting.

Lockaby, B.G., Governo, R., Rummer, B., and Colson, C. 2004. Silvicultural management within streamside management zones of intermittent streams: Effects on decomposition, productivity, nutrient cycling, and channel vegetation. *Southern Journal of Applied Forestry* 28(4)211-224.

ARKANSAS

Arkansas BMP Study: This study examined the effectiveness of Arkansas' silvicultural BMPs in protecting the water quality and biological integrity of streams adjacent to harvest areas. Bioassessment using benthic macroinvertebrate assemblages was the primary means by which potential environmental degradation was evaluated. Analyses revealed few significant differences in either water quality or biological variables that could be associated with silviculture. Differences between upstream and downstream sites, when noted, were present before as well as after timber harvest. Differences in relative abundance variables (e.g., percent EPT) were typically location-specific and unrelated to silviculture activities.

Grippo, R.S., and McCord, S.B. 2006. *Bioassessment of silvicultural best management practices in Arkansas*. Jonesboro, AR: Arkansas State University, College of Science and Mathematics. 206 pp.

FLORIDA

Intensive Management Practices Assessment Research Center: In 1976, the USDA Forest Service established an Intensive Management Practices Assessment Research Center with the University of Florida School of Forest Resources and Conservation and the forest industry to support joint cooperative research at the Austin Cary Memorial Forest. This multidisciplinary project helped develop Florida's BMPs to protect water quality in 1979. Today, the Forest Hydrology Section of the

Florida Forest Service is responsible for BMP development and implementation, as well as for monitoring BMPs for compliance and effectiveness.

http://www.fl-dof.com/forest_management/hydrology_index.html

Vowell 2001: The abstract to this paper is reprinted here.

> "A best management practices (BMPs) effectiveness study was conducted to evaluate Florida's BMPs for protecting aquatic ecosystems during intensive forestry operations. Sites were selected in major ecoregions of the state and each site was associated with a stream adjacent to intensive silviculture treatments. A stream bioassessment was conducted at each site before silviculture treatments, to determine a pre-treatment stream condition index (SCI). Sampling for the bioassessment was conducted at points along each stream, above and below the treatment area, to establish reference and test conditions. Silviculture treatments of clearcut harvesting, intensive mechanical site preparation and machine planting were then completed, during which all applicable BMPs were adhered to. One year after the first bioassessment and following the treatments, the sites were re-sampled at the same points. No significant difference in the SCI was observed between the reference and test portions of the streams that could be attributed to the treatments using BMPs."

Vowell, J.L. 2001. Using stream bioassessment to monitor best management practice effectiveness. *Forest Ecology and Management* 143:237-244. http://dx.doi.org/10.1016/S0378-1127(00)00521-1

GEORGIA

B.F. Grant Memorial Forest: In 1973, University of Georgia faculty began studies to evaluate the effects of harvesting and regeneration on the quality, quantity, and timing of water flows from Piedmont forests. The goal of this research was to provide forest managers with tools to predict hydrologic responses to harvesting and develop best management practices.

Fraser, N., Jackson, C.R., and Radcliffe, D.E. accepted. A paired watershed investigation of silvicultural BMPs revisited: BF Grant Memorial Forest, Georgia. *Forest Science*.

Hewlett, J.D. 1979. *Forest water quality: An experiment in harvesting and regenerating Piedmont forests*. Athens, GA: University of Georgia, School of Forest Resources Press.

Clinton and Vose 2003: A portion of the abstract is reprinted here.

> "We assessed differences in production of total suspended solids (TSS; ppm) from four road surface conditions in a Southern Appalachian watershed: (1) a 2-yr-old paved surface (P), (2) an improved gravel surface with controlled drainage and routine maintenance (RG), (3) an improved gravel surface with erosion and sediment control structures installed and routine maintenance (IG), and (4) an unimproved poorly maintained gravel surface (UG). Variation was high among and within road surface types. The P surface generated the least amount of TSS, which was comparable to control sites, while the UG surface generated the most. The P surface produced significantly less TSS than the UG surface, but not less than the IG and RG surfaces."

Clinton, B.D., and Vose, J.M. 2003. Differences in surface water quality draining four road surface types in the southern Appalachians. *Southern Journal of Applied Forestry* 27(2):100-106.

Depressional Wetland BMP Study: Soil accretion, sediment deposition, and nutrient accumulation were compared in floodplain and depressional freshwater wetlands of southwestern Georgia to evaluate the role of riverine versus depressional wetlands as sinks for sediment and nutrients. There was no significant difference in organic carbon, nitrogen, or sediment accumulation between depressional and floodplain wetlands. However, phosphorus accumulation was 1.5 to 3 times higher in the floodplains. Sediment and nutrient accumulations were highly variable among depressional wetland types, more so than between depressional and floodplain wetlands. Sediment and nutrient accumulations in these wetland types probably reflected the greater numbers of farms, greater grazing by livestock, and absence of environmentally sound agricultural practices in southwestern Georgia at the beginning of the 20th Century. These findings suggest that the degree of anthropogenic disturbance within the surrounding watershed regulates wetland sediment, organic carbon, and nitrogen accumulation rates.

Craft, C.B., and Casey, W.P. 2000. Sediment and nutrient accumulation in floodplain and depressional freshwater wetlands of Georgia, USA. *Wetlands* 20(2):323-332. http:dx.doi.org/10.1672/0277-5212(2000)020[0323:SANAIF]2.0.CO;2

Dry Creek–International Paper BMP Study: This paired watershed study used a before-after control-impact (BACI) design to assess impacts from timber harvesting in southwest Georgia. Two watersheds served as controls, two had commercial clearcuts with upper SMZs left intact, and a lower SMZ with partial harvesting followed Georgia BMPs. There were changes to baseflows and small changes in peak flows, as well as some changes in nutrients and elevated dissolved oxygen levels. "…current Georgia BMPs concerning SMZs appear to be effective to protect physical and chemical integrity of streams in the upper coastal plain headwaters." A shift in macroinvertebrate communities and an increase in macroinvertebrate populations were detected in response to some of the disturbances, but the values and costs of these changes are unknown. Sediment and herbicide data were also collected.

Miwa, M., Summer, W.B., Terrell, S.B., Griswold, M.W., Jones, D.G., Winn, R.T., and Bell, M. 2006. Timber harvesting effects on small headwater riparian wetlands in southwestern Georgia. In *Hydrology and management of forested wetlands: Proceedings of the international conference*, 99-106. ASAE Publication 701P0406. St. Joseph, MI: American Society of Agricultural and Biological Engineers.

Dry Creek–Stream Bio Index Study: Natural interannual and stream-to-stream variability in hydrology was significantly different even within sub-watersheds of a small catchment, which suggested that hydrology is an important environmental factor influencing stream ecology and should be considered in macroinvertebrate studies.

Winn, R.T. 2005. Aquatic macroinvertebrate assemblages in southwest Georgia headwater streams. MS thesis. University of Florida.

Dry Creek–Headwater Macroinvertebrate Study: Streams in thinned SMZs experienced increases in chlorophyll *a* and comparable reductions in stored organic matter compared to reference sites. In response, macroinvertebrate communities shifted from detritivores to herbivores. Although harvesting within SMZs altered community structure, indices of water quality based on macroinvertebrates suggested that the most favorable conditions occurred in the most disturbed SMZ treatments. This study suggests that properly managed riparian zones effectively maintain water quality in small coastal plain streams.

Griswold, M.W, Berzinis, R.W., and Crisman, T.L. in preparation. Functional changes in the biotic community structure of coastal plain streams (Georgia, USA) following selective harvest.

Dry Creek–Clay and Herbicide Transport Study: Streamwater samples were collected at two watersheds (B and C) within the Dry Creek Study area for determination of hexazinone, imazapyr, and sulfometuron methyl. Each site was equipped with an autosampler (ISCO Model #3700 with 1 L polypropylene bottles) for collecting samples during storm events. Grab samples were collected daily following herbicide applications. The maximum hexazinone concentration found in any single sample was 8.3 ppb one day after treatment (1 DAT), and base flow concentrations fell below 1 ppb by 16 DAT. The maximum imazapyr concentration found in any single sample was 7.3 ppb in a storm event sample 6 DAT. Imazapyr concentrations dropped below 1 ppb by 44 DAT. The highest sulfometuron methyl concentration detected in any sample was 1.2 ppb 1 DAT, and all sample analyses returned results below 1 ppb by 2 DAT.

National Council for Air and Stream Improvement, Inc. (NCASI). 2006. *Dissolved concentrations of hexazinone, imazapyr, and sulfometuron methyl in streamwater from the Dry Creek study site*. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

Dry Creek–Overland Flow Study: Water yields in two harvested watersheds increased by 30 to 316%. Storm event peak flows significantly increased for one pair of watersheds but decreased significantly for the other pair after harvest. Natural variance in sediment transport was high and no statistically significant response to harvesting and site preparation was observed. Evidence of concentrated overland flow entering SMZs and streams increased immediately after harvest in treatment watersheds, but was reduced within two years following harvest.

Terrell, S.B. 2008. Hydrologic and sediment transport responses to forest harvest and site preparation in headwater streams: South Georgia, USA. MS thesis. University of Georgia.

Rivenbark and Jackson 2004: SMZs of 30 recently harvested and site prepared units were surveyed for breakthrough points where flow and/or sediment moved through the SMZ and were delivered to streams or entered the SMZ but were not delivered to streams. The contributing areas represented about 5% of the units. Approximately 50% of the breakthroughs were at convergences (gullies and swales) and 25% were related to road or skid trail runoff.

A portion of the abstract is reprinted here.

> "Breakthroughs tended to occur in areas with large contributing areas, low litter cover, and steep slopes…Fourteen percent of the breakthroughs traveled more than 100 feet through the SMZs before reaching the streams. Results imply that reduction of bare ground, better dispersal of road runoff, introduction of hydraulic resistance to likely flow paths, and targeted extension of SMZ with may be warranted in improving BMPs on Piedmont forests."

Rivenbark, B., and Jackson, C. 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern Piedmont, USA. *Journal of the American Water Resources Association* 40(4):1043-1052. http://dx.doi.org/10.1111/j.1752-1688.2004.tb01065.x

Rummer, Stokes, and Lockaby 1997: A portion of the abstract is reprinted here.

> "Four surfacing treatments installed on two test roads included native soil, native soil with vegetative stabilization, 6cm of gravel, and 15cm of gravel over geotextile. During the first flooding season periodic sampling measured floodwater suspended sediments and location of erosion and sediment deposition within the road prism. Initial results suggest that sediment movement was confined to the road right-of-way, with no statistically significant sedimentation effects detected beyond the clearing limits of the road."

Rummer, B. 2004. Managing water quality in wetlands with forestry BMPs. *Water, Air, and Soil Pollution: Focus* 4:55-56. http://dx.doi.org/10.1023/B:WAFO.0000012826.29223.65

Rummer, B., Stokes, B. and Lockaby, G. 1997. Sedimentation associated with forest road surfacing in a bottomland hardwood ecosystem. *Forest Ecology and Management* 90:195-200. http://dx.doi.org/10.1016/S0378-1127(96)03904-7

Ward and Jackson 2005: The effectiveness of SMZs for two Georgia Piedmont clearcuts was assessed. "SMZ efficiencies for trapping sediment transported by concentrated flow ranged from 71 to 99 percent."

Ward, J., and Jackson, C. 2004. Sediment trapping within forestry streamside management zones: Georgia Piedmont, USA. *Journal of the American Water Resources Association* 40(6):1421-1431. http://dx.doi.org/10.1111/j.1752-1688.2004.tb01596.x

White et al. (2007): The authors tested the effectiveness of filter strips to reduce sediment delivery. A portion of the abstract is reprinted here.

> "Simulated runoff containing particle sizes ranging from colloidal-size clay to sand-size particles and aggregates was applied to forested filter strips in two conditions (undisturbed forest floor and forest floor removed by hand raking) across five slope classes (0% to 2%, 5% to 7%, 10% to 12%, 15% to 17%, and 20% to 22%) in the Piedmont of Georgia. Total sediment retention ranged from 53% to 96% and averaged 72% across all slope classes and conditions. Particles >20 μm (>0.00079 in) in diameter were largely retained in the first 2 m (6.6 ft) of the filter strip by settling. The runoff concentration of particles <2 μm (<0.000079 in) in diameter was not affected by the filter strips, but some retention occurred through infiltration. Retention of the 2- to 20-μm size fraction was correlated to flow distance within the filter strip. In areas of undisturbed forest floor, there was a correlation between forest floor depth and sediment retention. Forest floor removal decreased retention, but even where forest floor was removed, a majority of the applied sediment was retained. Our results indicate that narrow filter strips will effectively remove coarse-textured sediments >20 μm in diameter, and a 16-m (52-ft) wide filter strip should remove most 2- to 20-μm size sediments from runoff water."

White, W.J., Morris, L.A., Warnell, D.B., Pinho, A.P., Jackson, C.R., and West, L.T. 2007. Sediment retention by forested filter strips in the Piedmont of Georgia. *Journal of Soil and Water Conservation* 62:453-463.

KENTUCKY

Arthur, Coltharp, and Brown 1998: Two watersheds were harvested, one with BMPs and the other without. A third watershed served as a control. The fluxes of suspended sediment were 14 and 30 times higher on the BMP and non-BMP watersheds during the treatment compared to the control watershed. Sediment fluxes were 4.5 and 6 times above the control in the 17 months after treatment was completed. No change in temperature was found. "The streamside buffer strip was effective in reducing the impact of clearcutting on water yield and sediment flux."

Arthur, M.A., Coltharp, G.B., and Brown, D.L. 1998. Effects of best management practices on forest streamwater quality in eastern Kentucky. *Journal of the American Water Resources Association* 34(3):481-495. http://dx.doi.org/10.1111/j.1752-1688.1998.tb00948.x

Eiche and Barton 2011: This study followed up on Arthur, Coltharp, and Brown (1998), looking at long-term patterns of runoff and water quality for two treatment watersheds (with and without BMPs) and one control watershed. Increases in runoff from the treated watersheds had persisted for nearly three decades but were moderated by the riparian buffer for the BMP watershed compared to the watershed without BMPs. Most water quality effects declined four years after harvesting, but the monthly nitrate pattern appeared to be modified for the without-BMPs watershed compared to the other watersheds.

Eiche, N., and Barton, C. 2011. Long-term effects of BMPs in eastern Kentucky. Poster presented at the 2011 Society of American Foresters National Convention, Honolulu, HI.

Robinson Forest Streamside Management Zone Study: This study looked at protection of ephemeral streams. Treatments included no equipment limitation with complete overstory removal and unimproved crossings; no equipment limitations with retention of channel bank trees and improved crossings; and equipment restrictions within 7.6 m of the channel with retention of channel bank trees and improved crossings. Harvesting increased sediment movement within these channels. "All improved channel crossings reduced the amount of sediment input over that of an unimproved ford. However, the 7.6-m equipment restriction zone did not provide additional sediment reduction."

Witt, E.L., Barton, C.D., Stringer, J.W., Bowker, D.W., and Kolka, R.K. 2011. Evaluating best management practices for ephemeral channel protection following forest harvest in the Cumberland Plateau–Preliminary findings. In *Proceedings of the 17th Central Hardwood Forest Conference*, 365-374. General Technical Report NRS-P-78. Newtown Square, PA: United States Department of Agriculture Forest Service, Northern Research Station.

Svec, Kolka, and Stringer 2005: Flow duration was used to define appropriate BMPs, but delineation of streamflows based on maps can be inaccurate. Watershed area and channel characteristics were used to develop a robust predictor of the stream flow duration.

Svec, J.R., Kolka, R.K., and Stringer, J.W. 2005. Defining perennial, intermittent, and ephemeral channels in eastern Kentucky: Application to forestry best management practices. *Forest Ecology and Management* 214:170-182. http://dx.doi.org/10.1016/j.foreco.2005.04.008

LOUISIANA

Colyell Creek Study: This was a study of macroinvertebrate communities in Mill, Big Brushy, and Six-Mile Creeks in southwestern Louisiana.

> "The streams showed strikingly different seasonal patterns in dissolved oxygen concentration, discharge, temperature, and woody debris abundance, and data indicate that macroinvertebrates may follow a similar cycles. Importantly, this suggests that Louisiana streams may require multiple visits over multiple seasons to characterize and develop management strategies, particularly regarding biomonitoring activities…A small-scale riparian clearing was found to have negligible effects on downstream macroinvertebrate community composition, indicating that small-scale perturbations in these systems probably mimic historical impacts from fires and storms, with little long-lasting community effects."

http://www.reeis.usda.gov/web/crisprojectpages/189766.html

Flat Creek Study:

> "Timber harvest can increase streamwater temperature, surface runoff, organic input, and subsurface leaching of nutrients, which can reduce dissolved oxygen (DO) concentrations in adjacent water bodies. To limit water quality degradation, total maximum daily load (TMDL) guidelines are often set, requiring best management practice (BMP) implementation. Natural conditions in Louisiana have been shown to cause low stream DO concentrations. The goals of this study were to (1) test effectiveness of Louisiana's current BMPs at maintaining DO concentration at pre-harvest levels, and (2) to determine any necessary BMP additions/changes. The study took place in the Flat Creek watershed in North-central Louisiana. Two in-stream water quality monitoring sondes were deployed along a 2nd-order, low-gradient stream—one above and another below an area that was harvested using Louisiana's current BMPs. The sondes continuously measured DO concentration at 15-minute intervals from 2006 through 2009, during which harvest was conducted in 2007. In addition, monthly water samples from both locations were collected and analyzed for biochemical oxygen demand and total carbon. Marginal, but significant, increases in stream

flow, water temperature, total carbon, and BOD were found following harvest. However, stream DO concentrations either stayed at pre-harvest levels, or even slightly (but significantly) increased. For the majority of the four years, concentrations of DO were below the EPA recommendation of 5 mg L-1. The results indicate that the BMPs implemented are effective at maintaining DO concentration at pre-harvest levels, though minimum DO concentration limits may be unattainable due to natural stream and watershed features."

DeSilva, A., Xu, Y.Y., Beebe, J., and Ice, G.G. 2010. Dissolved oxygen analysis of a northern Louisiana headwater stream during timber harvesting operations. In *Proceedings of the TMDL 2010: Watershed Management to Improve Water Quality*. CD-ROM Proceedings 711P0710cd. St Joseph, MI: American Society of Agricultural and Biological Engineers.

http://www.awra.org/committees/techcom/watershed/pdfs/0302WU.pdf

Louisiana Tech BMP Study:

"Nine tracts with upstream and downstream monitoring and sampling stations were established in the Upper Dugdemona and Castor Creek USGS Hydrologic Units (watersheds) in Bienville, Jackson, and Winn Parishes in 2004-5. Three of the tracts had the Control/No Harvest treatment; three tracts were the Harvest with BMPs treatment; and three tracts received the Harvest with no BMPs treatment…No Harvest and Harvest with BMP treatment tracts had higher turbidity levels upstream of the treatment than downstream of the treatment, both before and after the treatment. The Harvest without BMPs treatment had significantly higher downstream turbidity levels relative to upstream levels in the post-harvest period. Although nutrient levels were not significantly different between treatments, downstream total nitrogen levels greatly exceeded upstream levels, before and after treatment, even in the No Harvest treatment…The storm sampled water quality data were compared to proposed water quality standards. In the pre-harvest period, 46.8% of water samples had impaired levels of turbidity, total nitrogen, and total phosphorus. The post-harvest period had 58.8 % of the samples classified as impaired. The No Harvest treatment in the post-harvest period had a 51% impairment rate for the combined parameters."

http://www.reeis.usda.gov/web/crisprojectpages/218816.html

MISSISSIPPI

Keim and Schoenholtz 1999: This was a study of the effectiveness of SMZs in protecting water quality in the Deep Loess Region of Mississippi. An unrestricted harvest near the stream resulted in increased total suspended solids (TSS).

"Skidder traffic in the unrestricted harvest increased exposure of mineral soil in the riparian area immediately after logging by 1.4 to 2.0 times that of other treatments…Results indicate that SMZs did not serve to filter sediment from overland flow, but their effectiveness in reducing TSS was probably due to exclusion of disturbance to the forest floor near the stream and to the stream itself."

Keim, R.F., and Schoenholtz, S.H. 1999. Functions and effectiveness of silvicultural streamside management zones in loessial bluff forests. *Forest Ecology and Management* 118:197-209. http://dx.doi.org/10.1016/S0378-1127(98)00499-X Erratum: *Forest Ecology and Management* 123:91.

Carroll et al. 2004:

> "Three SMZ treatments (undisturbed reference, clear-cut logging with an SMZ designated by forest managers, or clear-cut logging with no SMZ) were evaluated using a study with three replications of each treatment. Response metrics including water quality parameters, mineral soil exposure and net deposition/erosion within riparian zones, stream habitat indicators, and aquatic macroinvertebrate communities were comparable between streams receiving SMZs and undisturbed reference streams at all sampling intervals during the first year after treatment. Furthermore, significant elevation of streamwater temperature, decline in habitat stability rating, and increase in density of macroinvertebrates occurring in streams without an SMZ in comparison to reference streams provides additional evidence of SMZ effectiveness during the initial year after harvesting."

Carroll, G.D., Schoenholtz, R.B., Young, B.W., and Dibble, E.D. 2004. Effectiveness of forestry streamside management zones in the Sand-Clay Hills of Mississippi: Early indications. *Water, Air, and Soil Pollution: Focus* 4(1):275-296. http://dx.doi.rog/10.1023/B:WAFO.0000012813.94538.c8

NORTH CAROLINA

Appelboom et al. 2002: Berms reduced sediment losses from forest roads in the coastal plains. This control only worked for low gradient sites.

Appelboom, T.W., Chescheir, G.M., Skaggs, R.W., and Hesterberg, D.L. 2002. Management practices for sediment reduction from forest roads in the Coastal Plains. *Transactions of the American Society of Agricultural Engineers* 45(2):337-342.

Coweeta Hydrologic Laboratory: The Coweeta Research Work Unit was created in 1934 to study how forests affect the streams that flow through them. This 5400-acre experimental forest was established in Otto, North Carolina, because of the basin's high rainfall amounts and mountainous topography. Today, as part of the USDA Forest Service Southern Research Station, Coweeta Hydrologic Laboratory research focuses on the broad areas of land use and water quality, climate change, and prescribed fire. Over 75 years of research has generated numerous publications on BMPs designed to limit the production and movement of sediment from forest roads and trails.

http://www.srs.fs.usda.gov/coweeta/publications/

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

Swift, L.W. Jr. 1985. Forest road design to minimize erosion in the southern Appalachians. In *Proceedings of Forestry and Water Quality: A mid-South symposium*, ed. B.G. Blackmon, 141-152. Little Rock, AR: University of Arkansas Extension.

Swift, L.W. Jr. 1986. Filter strip widths for forest roads in the southern Appalachians. *Southern Journal of Applied Forestry* 10(1):27-34.

Lebo and Herrmann 1998: This study looked at the effects of timber harvesting in pocosins in North Carolina. Harvesting resulted in small changes in water quality, particularly for nutrients, but increases in discharge following harvesting resulted in increased fluxes of both sediment and nutrients out of the watersheds. The small impacts on water quality returned to baseline within three years. Amatya et al. (1998) found that controlled drainage could reduce both runoff and losses of sediment and nutrients.

Amatya, D.M, Gilliam, J.W., Skaggs, R.W., Lebo, M.E., and Campbell, R.G. 1998. Effects of controlled drainage on forest water quality. *Journal of Environmental Quality* 27:923-935. http://dx.doi.org/10.2134/jeq1998.00472425002700040029x

Lebo, M.E., and Herrmann, R.B. 1998. Harvest impacts on forest outflow in coastal North Carolina. *Journal of Environmental Quality* 27:1382-1395. http://dx.doi.org/10.2134/jeq1998.00472425002700060015x

South Appalachian Buffer Width Study: The objective of this paired watershed study was to quantify the effects of upland forest harvesting and SMZs on stream water quantity and quality in North Carolina. Watersheds with perennial stream channels were gauged for flow monitoring and water quality sampling. The study started in 2007, and the first two years were used to calibrate watershed runoff and stream water quality. During Year 3, one watershed from each pair was clearcut with the exception of the SMZs, which were maintained according to the Neuse River Buffer Rules (50 ft buffer along streams).

Boggs, J.L., Sun, G., Summer, W., McNulty, S.G., Swartley, W., and Treasure, E. 2008. Effectiveness of streamside management zones on water quality: pretreatment measurements. In *AWRA summer specialty conference*, 1-6. June 30-July 2, Virginia Beach, VA. American Water Resources Association.

OKLAHOMA

Weyerhaeuser Paired Watershed Study:

> "Clear-cut harvest and site preparation, including crushing the residual vegetation, burning, and contour ripping, were applied to three small watersheds in Oklahoma. Three undisturbed forested watersheds served as controls. First-year sediment losses averaged 282 and 36 kg/ha and storm flow water yields averaged 22.9 and 31.7 cm on clear-cut and uncut watersheds, respectively. The lower water yield on cut watersheds may have been due to contour ripping. Treatment differences in sediment yield were significant the second and third, but not the fourth, year following treatment. Storm flow water yield from clear-cut watersheds was significantly higher than from uncut watersheds the second year but not the third or fourth years. Absolute levels of sediment yield from clear-cut and control watersheds were relatively low in all years of the study. The overall impact of harvest and site preparation on total suspended solids levels in runoff was small and short-lived."

Miller, E.L. 1984. Sediment yield and storm flow response to clearcut harvest and site preparation in the Ouachita Mountains. *Water Resources Research* 20(4):471-475. http://dx.doi.org/10.1029/WR020i004p00471

SOUTH CAROLINA

Adams, Hook, and Floyd: A series of papers on testing BMP effectiveness and compliance in South Carolina are available.

For this study, 175 harvest sites were evaluated for compliance with state BMPs, and overall compliance was 84.7%.

> "The lack of compliance with silvicultural BMPs was primarily caused by a failure of all landowners to identify and adequately protect sensitive sites…The most critical management

decision which affected BMP compliance was the timing of logging during periods of wet soil conditions."

Adams, T.O., and Hook, D.D. 1994. Compliance with silvicultural best management practices on harvested sites in South Carolina. *Southern Journal of Applied Forestry* 18(4):163-167.

Rapid Bioassessment Protocols were compared to BMP compliance.

"The results indicate that a weight-of-evidence approach utilizing a BMP compliance check, a stream habitat assessment, and a benthic macroinvertebrate bioassessment is the most accurate method of evaluating BMP effectiveness. These data show that implementation of BMPs during harvest operations was sufficient for the protection of the water quality of associated streams."

Adams, T.O., Hook, D.D., and Floyd, M.A. 1995. Effectiveness monitoring of silvicultural best management practices in South Carolina. *Southern Journal of Applied Forestry* 19(4):170-176.

This study focused on compliance with site preparation BMPs. Overall BMP compliance was 86.4%, with 22 out of 24 inadequate sites located in the Piedmont Region of South Carolina. One concern was that site preparation prescriptions appeared to be based on overall slope rather than on critical slopes in treatment units.

Adams, T.O. 1998. Implementation monitoring of forestry best management practices for site preparation in South Carolina. *Southern Journal of Applied Forestry* 22(2):74-80.

Williams et al. 2000: This research compared sediment losses from contemporary forestry with BMPs to loggers' choice harvesting impacts on another set of Piedmont watersheds (Hewlett 1979 in Grant Forest, Georgia). Observed sediment losses were about 10% of those reported by Hewlett.

Williams, T.M., Hook, D.D., Lipscomb, D.J., Zeng, X., and Albiston, J.W. 2000. Effectiveness of best management practices to protect water quality in South Carolina Piedmont. In *Tenth biennial southern silvicultural research conference*, 271-277. General Technical Report SRS-30. Asheville, NC: United States Department of Agriculture Forest Service.

TENNESSEE

Cow Hollow Branch Watershed: Between early 2004 and late 2007, approximately 70% of this watershed was clearcut. Despite this, the substrate of Cow Hollow Branch has remained free of new mineral sediment deposits. The macroinvertebrate community remains at a level of "exceptional biological diversity," and Cow Hollow Branch retains its status as Tennessee Exceptional Waters.

Wilder, T.C., and Augustin, J.C. 2008. *Clear-cut within the watershed of a high quality stream of the western highland rim: Analysis of five years of macroinvertebrate data*. Columbia, TN: Tennessee Department of Environment and Conservation, Division of Water Pollution Control.

Picket State Forest: Three stands were harvested in Picket State Forest, with BMPs implemented to protect Rock Creek and Little Rock Creek. Water quality, macroinvertebrate communities, and fish populations of the treated areas and adjacent streams were monitoring before, during, and after harvest. Monitoring indicated no detrimental impacts from the harvesting to these response variables. A small transient change in TSS was detected for Little Rock Creek.

Curtis, J.G., Pelren, D.W., George, D.B., Adams, V.D., and Layzer, J.B. 1990. *Effectiveness of best management practices in preventing degradation of streams caused by silvicultural activities in Picket State Forest, Tennessee*. Crookeville, TN: Tennessee Technological University, Center for Management, Utilization and Protection of Water Resources.

TEXAS

Alto Watershed Project (TexIS): From the mid-1970s to early 1980s, a series of experimental watershed studies were initiated in Arkansas, Oklahoma, and Texas to quantify sediment and erosion rates resulting from intensive forest management. The Alto Watershed site in the Gulf Coastal Plain of East Texas was revisited in the late 1990s to assess the effectiveness of Texas' forestry BMPs. This study provided an opportunity to measure erosion rates from roads and to evaluate road BMP effectiveness. Four large watersheds that were part of the study were assessed to determine the proportion of sediment coming from the road network compared to total sediment losses from the watersheds. Information on the Alto Study experimental design and research metrics can be found at the website.

http://www.fri.sfasu.edu/index.php?option=com_content&view=article&id=72:alto-watershed-project&catid=9:research-projects&Itemid=9.

Publications Addressing BMPs and Roads

McBroom, M. 2011. Texas Alto Watershed Study – Road sediment and watershed loss rates. Presented at the NCASI Southern Regional Meeting – Workshop on Forest Roads and Skid Trails in the South. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

McBroom, M.W., Beasley, R.S., Chang, M., and Ice, G.G. 2008. Storm runoff and sediment losses from forest clearcutting and stand re-establishment. *Hydrological Processes* 22(10):1509-1522. http://dx.doi.org/10.1002/hyp.6703

Other Key Publications from This Work

McBroom, M.W., Beasley, R.S., Chang, M., and Ice, G.G. 2008. Water quality effects of clearcut harvesting and forest fertilization with best management practices. *Journal of Environmental Quality* 37:114-124. http://dx.doi.org/10.2134/jeq2006.0552

McBroom, M.W., Louch, J., Beasley, R.S., Chang, M., and Ice, G. in review. Water quality effects of silvicultural herbicide applications with best management practices. *Forest Science*.

Texas Forest Service BMP Effectiveness Study: Four streams were monitored using a BACI study design to assess the effectiveness of Texas BMPs to protect water quality. Biological and physiochemical monitoring (both grab samples and stormwater samples) was conducted above and below treatment areas. The physiochemical data showed no statistically significant difference as a result of treatment. Following treatment, the biological data showed a shift in habitat quality at two sites and for fish at another site compared to the reference. Although change was detected, the treatment sites showed generally improved conditions for Aquatic Life Use (fish) and Habitat Quality Index. Treatment had no negative effect on water quality and biology.

http://txforestservice.tamu.edu/uploadedFiles/Sustainable/bmp/BMP%20Eff%20Mon%20final%20report-new%20format-for%20website1.pdf

VIRGINIA

Virginia Tech Watershed Research Program: Several research projects evaluating forest road and stream crossing BMP effectiveness have been conducted by researchers at Virginia Polytechnic Institute. Some recent findings are included here.

Aust, W.M., Carroll, M.B., Bolding, M.C., and Dolloff, C.A. 2011. Operational forest stream crossings effects on water quality in the Virginia Piedmont. *Southern Journal of Applied Forestry* 35(3):123-130.

Sawyers, B.C., Bolding, M.C., Aust, W.M., and Lakel, W.A. III. (in press). Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia piedmont. Accepted 10/31/11 by *Journal of Soil and Water Conservation*.

Wade, C.R., Bolding, M.C., Aust, W.M., and Lakel, W.A. III. (in press). Comparison of five erosion control techniques for bladed skid trails in Virginia. Accepted 09/06/11 by *Southern Journal of Applied Forestry*.

Worrell, M., Bolding, C., and Aust, W.M. 2011. Potential soil erosion following skyline versus tracked skidding on bladed skid trails in the Appalachian region of Virginia. *Southern Journal of Applied Forestry* 35(3):131-135.

VT-MW BMP Study: This study compared the effects of SMZ widths and thinning levels on sediment moving through riparian areas. Four SMZ treatments were installed within 16 harvested watersheds where intermittent streams graded into small perennial streams. Sites were clearcut, prescribed burned, and planted with loblolly pine. Treatments were 30.4, 15.2, and 7.6 m wide SMZs without thinning and 15.2 m wide SMZs with thinning. SMZ treatments had no significant differences in sediment trapping; all SMZs widths were generally effective in trapping sediment. Erosion to sediment delivery ratios from harvests ranged from 3 to 14%. For ephemeral stream sub-watersheds, firelines adjacent to SMZs contributed 14% of total sediment. Sediment trap data collected within SMZs indicated that 97% of watershed erosion was trapped before reaching streams.

Lakel, W.A. III, Aust, W.M., Bolding, M.C., Dolloff, C.A., Keyser, P., Feldt, R. Jr. 2010. Sediment trapping by streamside management zones of various widths following harvest and site preparation. *Forest Science* 56(6):541-551.

Wynn et al. 2000: Three small watersheds were monitored to assess the impacts of clearcutting and site preparation with and without BMPs.

> "Storm event concentrations and loadings of sediment, nitrogen, and phosphorus increased significantly following forest clearcutting and site preparation of the NO-BMP watershed. Both the BMP watershed and the Control watershed showed few changes in pollutant storm concentrations or loadings throughout the study. Results of this study indicate forest clearcutting and site preparation without BMPs can cause significant increases in sediment and nutrient concentrations and loading in the Virginia Coastal Plain. However, these impacts can be greatly reduced by implementing a system of BMPs on the watershed during harvesting activities."

Wynn, T.M., Motaghimi, S., Frazee, J.W., McClellan, P.W., Shaffer, R.M., and Aust, W.M. 2000. Effects of forest harvesting best management practices on surface water quality in the Virginia Coastal Plain. *Transactions of the American Society of Agricultural Engineers* 43:927-936.

WEST VIRGINIA (See Appendix B)

APPENDIX B

KEY SOURCES OF INFORMATION ON FORESTRY BEST MANAGEMENT PRACTICES EFFECTIVENESS RESEARCH IN THE NORTH

This appendix provides references, website addresses, and other information for key research on forest best management practice (BMP) effectiveness conducted in the northern United States. For other summary information on this subject, see Edwards and Willard (2010); Huyler, McMath, and Hewitt (1999); and papers in Ice and Stednick (2004) by Verry and by Hornbeck and Kochenderfer.

Edwards, P.J., and Willard, K.W.J. 2010. Efficiencies of forestry best management practices for reducing sediment and nutrient losses in the eastern United States. *Journal of Forestry* 108(5):245-249.

Huyler, N.K., McMath, D., and Hewitt, D. 1999. *Annotated bibliography on forest practice legislation related to water quality*. General Technical Report NE-258. Radnor, PA: United States Department of Agriculture Forest Service, Northeastern Research Station.

Ice, G.G., and Stednick, J.D. (eds.) 2004. *A century of forest and wildland watershed lessons*. Bethesda, MD: Society of American Foresters.

CONNECTICUT

Maynard and Hill 1992: This study looked at practices needed to re-establish vegetation to control erosion and avoid invasive plant development, especially for logging in suburban settings.

Maynard, A.A., and Hill, D.E. 1992. Vegetative stabilization of logging roads and skid trails. *Northern Journal of Applied Forestry* 9:153-157.

[In addition, see Hornbeck, Martin, and Smith (1986) in the Maine section.]

MAINE

Briggs, Kimball, and Cormier 1998: This was an assessment of BMP compliance and effectiveness in Maine. “When BMPs were used, sediment movement was eliminated completely or was largely restricted from surface waters. Numbers of sites at which appreciable sediment delivery to surface waters was associated with noncompliance of individual BMPs.” Old roads were reported to be a challenge.

Briggs, R.D., Kimball, A.J., and Cormier, J. 1998. Compliance with forestry best management practices in Maine. *Northern Journal of Applied Forestry* 15(2):57-68.

Hornbeck, Martin, and Smith 1986: The authors studied whole-tree harvesting in Maine, New Hampshire, and Connecticut. “Changes in stream quality can be expected as a result of whole-tree harvesting, but common-sense precautions…can keep the changes within acceptable levels.” Increases in turbidity, stream temperature, and nitrate-nitrogen were observed for some control-treatment pairs. Some practical practices to minimize negative water quality impacts were suggested.

Hornbeck, J.W., Martin, C.W., and Smith, C.T. 1986. Protecting forest streams during whole-tree harvesting. *Northern Journal of Applied Forestry* 3:97-100.

Manomet Riparian Study: An experiment tested alternative buffer treatments for first-order headwater streams in western Maine. Treatments included no buffer; clearcut with 11 m partially harvested buffers on both sides; clearcut with 23 m partially-harvested buffers; partial cuts with no designated buffers; and unharvested controls. Streams with 11 m buffers showed minor but not statistically significant increases in temperature.

http://www.manomet.org/science-applications/natural-capital/headwater-stream-project

Wilkerson, E., Hagan, J.M., Siegel, D., and Whitman, A.A. 2006. The effectiveness of different buffer widths for protecting headwater stream temperature in Maine. *Forest Science* 52(3):221-231.

Pierce et al. 1993: A USDA Forest Service General Technical Report summarized research on reducing impacts to streams in the Northeast.

Pierce, R.S., Hornbeck, J.W., Martin, C.W., Tritton, L.M., Smith, C.T., Federer, C.A., and Yawney, H.W. 1993. *Whole-tree clearcutting in New England: Manager's guide to impacts on soils, streams and regeneration*. General Technical Report NE-72. Radnor, PA: United States Department of Agriculture Forest Service, Northeastern Forest Experiment Station.

MARYLAND

Doyle, Wolf, and Bezdicek 1975: This study looked at transport of livestock manure pollution through a forested buffer.

Doyle, R.C., Wolf, D.C., and Bezdicek, D.F. 1975. Effectiveness of forest buffer strips in improving the water quality of manure polluted runoff. In *Managing livestock wastes: Proceedings of the 1975 International Symposium on Livestock Wastes*, 299-302. St. Joseph, MI: American Society of Agricultural Engineers.

Maryland DNR BMP Study: This paired watershed study tested the effectiveness of Maryland BMPs using bi-weekly baseflow and stormwater monitoring. Sediment, temperature, and macroinvertebrate communities all showed no significant changes compared to a control watershed.

http://dnr.state.md.us/forests/mbmp/

MICHIGAN

Trettin, et al. 1997: This study examined the effects of harvesting on wetland functions in a sub-boreal Michigan wetland.

Trettin, C.C., Jurgensen, M.F., McLaughlin, J.W., and Gale, M.R. 1997. Effects of forest management on wetland functions in a sub-boreal swamp. In *Northern forested wetlands: Ecology and management*, ed. C.C Trettin, M.F. Jurgensen, D.F. Grigal, M.R. Gale, and J.K. Jeglum, 411-428. Boca Raton, FL: CRC Press.

MINNESOTA

Legislative-Citizen Commission on Minnesota Resources (LCCMR) Study: Modeling of watershed impacts was a minor component of this study of alternative biomass harvesting impacts on the ecology of Minnesota aspen forests, with sites established on nutrient-poor soils.

http://www.lccmr.leg.mn/PeerReview/2011/addendums/subd_3k_damato.pdf

Pokegama Creek Riparian Studies: The effects of alternative riparian harvesting on water quality and fish were studied. Few changes associated with the alternative riparian treatments were noted, but there was a decline in fish due to basin-scale impacts. Results may have been affected by a poorly designed stream crossing above multiple treatment segments (Chizinski et al. 2010).

http://www.frc.state.mn.us/documents/council/MFRC_Evaluating_Riparian_Area_Dynamics_1998-12-01_Report.pdf

Blinn, C.R., Palik, B.J., Newman, R.M., and Hanowski, J.M. 2001. *Evaluating timber harvesting and forest management guidelines: A project proposal to the Legislative Commission on Minnesota Resources*. St. Paul, Minnesota: University of Minnesota, Department of Forest Resources.

Chizinski, C.J., Vondracek, B., Blinn, C.R., Newman, R.M., Atuke, D.M., Fredricks, K., Hemstad, N.A., Merten, E., and Schlesser, N. 2010. The influence of partial timber harvesting in riparian buffers on macroinvertebrate and fish communities in small streams in Minnesota, USA. *Forest Ecology and Management* 259:1946-1958. http://dx.doi.org/10.1016/j.foreco.2010.02.006

Hemstad, N.A., Merten, E.C., and Newman, R.M. 2008. Effects of riparian forest thinning by two types of mechanical harvest on stream fish and habitat in northern Minnesota. *Canadian Journal of Forest Research* 38(2):247-256. http://dx.doi.org/10.1139/X07-157

Schlesser, N.J., Atuke, D.M., Vondracek, B., and Newman, R.M. 2004. Effects of riparian forest harvest on habitat and fish assemblages in northern Minnesota. Poster presented at the 65th Annual Midwest Fish and Wildlife Conference, Indianapolis, IN.

MISSOURI

MDC REAM Study: This BMP effectiveness study involved five control watersheds and ten treatment watersheds. No difference was observed in sediment for the treated watersheds with BMPs and the control watersheds.

http://www.privatelandownernetwork.org/exchange/pun.aspx?id=641

NEW HAMPSHIRE

Cullen 1991: Reduced erosion from forest activities was a result of increased implementation of BMPs.

Cullen, J.B. 1991. *Best management practices for erosion control on timber harvesting operations in New Hampshire*. Concord, NH: Department of Resources and Economic Development, Division of Forests and Lands.

DeHart 1982: Erosion rates on roads and landings at seven sites (10%) exceeded the T-value of 3 t/a/yr, but were <1 t/a/yr averaged over the entire harvest areas. Most erosion from unmanaged watersheds came from the channels.

DeHart, D.B. 1982. *The effects of timber harvesting on erosion and sedimentation in New Hampshire*. Concord, NH: New Hampshire Division of Forests and Lands, Department of Resources and Economic Development.

Hornbeck et al. 1986: This study focused on nutrient losses from strip cutting and block clearcutting. Both treatments resulted in increased nutrient losses. However, the authors concluded that "with careful logging and continued use of intervals of 70 to 120 years between harvests, clearcutting of northern hardwoods should not have adverse impacts on site nutrient capital."

Hornbeck, J.W., Martin, C.W., Pierce, R.S., Bormann, F.H., Likens, G.E., and Eaton, J.S. 1986. Clearcutting northern hardwoods: Effects on hydrologic and nutrient ion budgets. *Forest Science* 32(3):667-686.

[In addition, see Hornbeck, Martin, and Smith (1986) in the Maine section.]

Martin and Hornbeck 1994: A demonstration study of sediment yields and turbidity response followed harvesting using BMPs at the Hubbard Brook Experimental Forest. A list of BMPs was provided.

> "The treatment of WS 2 was experimental and did not reflect the usual kinds of harvest taking place in New England, and was more severe as a result of herbicide applications for 3 yr in succession. But it demonstrates that erosion can occur on watershed where no equipment has disturbed the soil, if buffer strips of trees are not left along the streams to provide wood debris and foliage to maintain the debris dams after cutting…Erosion, sedimentation, and turbidity need not be a major concern in New England forests if BMPs are followed closely."

Martin, C.W., and Hornbeck, J.W. 1994. Logging in New England need not cause sedimentation of streams. *Northern Journal of Applied Forestry* 11:17-23.

Martin and Pierce 1980: Forest watersheds that were clearcut had increased nitrate-nitrogen losses compared to unharvested watersheds. Calcium concentrations also rose. "Clearcutting less than entire watersheds and leaving buffer strips along the streams reduced the magnitude and duration of increases in concentrations."

Martin, C.W., and Pierce, R.S. 1980. Clearcutting patterns affect nitrate and calcium in streams of New Hampshire. *Journal of Forestry* 78(5):268-276.

NEW YORK

Paashaus, Briggs, and Ringler 2004: The authors used macroinvertebrate sampling to monitor ephemeral stream water quality in partially harvested and reference watersheds in the Catskill Mountain Region of southern New York. A variety of diversity indices showed no evidence that partial harvest using BMPs negatively impacted aquatic communities or water quality. Within the reference sites, the structures of macroinvertebrate communities varied greatly between years.

Paashaus, E.J., Briggs, R.D., and Ringler, N.H. 2004. Partial cutting impacts on macroinvertebrates in ephemeral streams in southern NY. In *Forestry across borders – Proceedings of the New England Society of American Foresters 84th Winter Meeting*, ed. J.S. Ward and M.J. Twery, 38-40. General Technical Report NE-314. Newtown Square, PA: United States Department of Agriculture Forest Service, Northeastern Research Station.

Schuler and Briggs 2000: In New York, implementation rates for 42 suggested BMPs were 78% for haul roads, 87% for landings, 59% for skid trails, 88% for equipment maintenance/operation, and 73% for buffer strips. Departures were common for BMPs concerned with stream crossings and with draining water off haul roads and skid trails; thus, the authors concluded that more attention must be devoted to those practices. BMPs were reported to be effective when they were applied correctly.

Schuler, J.L., and Briggs, R.D. 2000. Assessing application and effectiveness of forestry best management practices in New York. *Northern Journal of Applied Forestry* 17(4):125–134.

Wang et al. 2006: The authors reported small changes in stream water chemistry following a 2002 partial harvest with BMPs of a catchment in the Catskill Mountains of southern New York. Streamwater chemistry concentrations increased significantly after harvest treatments, and peak concentrations were reached five months or more after initiation of the harvest. Streamwater chemistry returned to values similar to those of the pre-harvest period and to reference levels by early spring 2003. Nitrate concentrations, however, remained elevated above background levels for approximately 18 to 20 months after harvest.

Wang, X., Burns, D.A., Yanai, R.D., Briggs, R.D., and Germain, R.H. 2006. Changes in stream chemistry and nutrient export following a partial harvest in the Catskill Mountains, New York, USA. *Forest Ecology and Management* 223:103-112. http://dx.doi.org/10.1016/j.foreco.2005.10.060

PENNSYLVANIA

Lynch, Rishel, and Corbett 1984: This was a study of temperature response to disturbance in forest streams. "Summer maximum stream temperatures averaged 1°C higher in the commercial clearcut and 9°C higher in the clearcut-herbicided watershed than in the forested control." Information about minimum temperatures was also provided.

Lynch, J.A., Rishel, G.B., and Corbett, E.S. 1984. Thermal alterations of streams draining clearcut watersheds: Quantification and biological implications. *Hydrobiologia* 111:161-169. http://dx.doi.org/10.1007/BF00007195

Lynch, Corbett, and Mussallem 1985: This watershed study conducted in central Pennsylvania suggested that BMPs were effective in controlling non-point source pollution from a 44.5 ha commercial clearcut. BMPs included protective buffer strips; a prohibition on skidding over streams; supervision of logging by a qualified forester; division of timber sales into blocks, with cutting restricted to one block at a time; no disposal of tops or slash within 8 m of streams; proper location of haul roads, skid trails, and log landings; retirement of skid trails, haul roads, and culverts after logging; and posting of a performance bond prior to logging. Slight increases in stream temperature, turbidity, and nitrate and potassium concentrations were observed, but did not exceed drinking water standards. The authors concluded that the slight increases in temperature and nutrients may have been temporarily beneficial to the aquatic ecosystem.

Lynch, J.A., Corbett, E.S., and Mussallem, K. 1985. Best management practices for controlling nonpoint-source pollution on forested watersheds. *Journal of Soil and Water Conservation* 40(1):164-167.

Lynch and Corbett 1990: Water quality impacts of a 110-acre harvest in a 257-acre watershed were monitored. "Overall, the BMPs employed on this commercial clearcut were very effective in preventing serious deterioration of stream quality as a result of forest harvesting." There were statistically significant changes in nitrate, potassium, temperature, and turbidity as a result of the harvest.

Lynch, J.A., and Corbett, E.S. 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. *Water Resources Bulletin* 26(1):41-52. http://dx.doi.org/10.1111/j.1752-1688.1990.tb01349.x

Miller et al. 1997: A survey of 70 forest road crossings of wetlands in Pennsylvania described the characteristics of the crossings and evaluated their long-term impacts on habitat quality, channel stability, vegetation, wetland width, and channel sediment embeddedness above and below the crossings. Only 35 of 814 comparisons of mean environmental conditions above and below the wetland crossings were found to be significant. Significant differences that did occur suggested that stream bed fine sediment levels were higher, basal area was lower, and herbaceous cover was higher in the immediate vicinity of some crossings due to the presence of the road and fill banks.

Miller, R.L. Jr., Dewalle, D.R., Brooks, R.P., and Finley, J.C. 1997. Long-term impacts of forest road crossings of wetlands in Pennsylvania. *Northern Journal of Applied Forestry* 14(3):109-116.

Rishel, Lynch, and Corbett 1982: This study tested the maximum potential for a change in stream temperature as a result of exposing the stream to direct solar radiation. A watershed that was clearcut and treated with herbicide had a maximum temperature following treatment of 32°C. A control watershed had a maximum of 22°C. A commercial clearcut with a buffer had a maximum of 23°C. Changes in minimum temperatures and diurnal temperature fluctuations were also reported for the clearcut/herbicide treated stream.

http://www.fs.fed.us/ne/global/ltedb/catalogs/cat80.html

Rishel, G.B., Lynch, J.A., and Corbett, E.S. 1982. Seasonal stream temperature changes following forest harvest. *Journal of Environmental Quality* 11(1):112-116. http://dx.doi.org/10.2134/jeq1982.00472425001100010026x

VERMONT

Brynn and Clausen 1991: This study involved a random sample of 78 completed harvesting operations in Vermont. None of the truck roads and only 20% of the skid roads had properly spaced drainage structures, but impacts on water quality were judged to be negligible. Compliance with other acceptable management practices (AMPs) was high.

Brynn, D.J., and Clausen, J.C. 1991. Postharvest assessment of Vermont's acceptable silvicultural management practices and water quality impacts. *Northern Journal of Applied Forestry* 8:140-144.

WEST VIRGINIA

Fernow Experimental Forest: The Fernow Experimental Forest was established in 1933 on Elk Lick Watershed in the mountains of West Virginia because of an emerging need to address the connection between silviculture and watershed management. Watershed research at Fernow has addressed basic questions about water use by forests and forest hydrology, as well as critical issues affecting roads, BMPs, and forest management effects on water and soil resources. Adams et al. (2004) provided a summary of the more than 50 years of research conducted at Fernow. The list of reports below includes several that address road BMPs. For additional information, visit http://www.nrs.fs.fed.us/ef/locations/wv/fernow/

Adams, M.B., Edwards, P.J., Kochenderfer, J.N., and Wood, F. 2004. Fifty years of watershed research on the Fernow Experimental Forest, WV: Effects of forest management and air pollution on hardwood forests. In *First interagency conference on research in the watersheds*, ed. K.G. Renard, S.A. McElroy, W.J. Gburek, H.E. Canfield, and R.L. Scott, 391-396. October 27-30, 2003, Benson, AZ. Tucson, AZ: United States Department of Agriculture Agricultural Research Service, Southwest Watershed Research Center.

Helvey, J.D., and Kochenderfer, J.N. 1988. Culvert sizes needed for small drainage areas in central Appalachians. *Northern Journal of Applied Forestry* 5:123-127.

Kochenderfer, J.N. 1970. *Erosion control on logging roads in the Appalachians*. Research Paper NE-158. Upper Darby, PA: United States Department of Agriculture Forest Service, Northeastern Forest Experiment Station.

Kochenderfer, J.N. 1995. *Using open-top pipe culverts to control surface water on steep road grades*. General Technical Report NE-194. Radnor, PA: United States Department of Agriculture Forest Service, Northeastern Forest Experiment Station.

Kochenderfer, J.N., Edwards, P.J., and Wood, F. 1997. Hydrologic impacts of logging an Appalachian watershed using West Virginia's best management practices. *Northern Journal of Applied Forestry* 14(4):207-218.

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

Kochenderfer, J.N., and Hornbeck, J.W. 1999. Contrasting timber harvesting operations illustrate the value of BMPs. In *Proceedings, 12th Central Hardwood Forest Conference*, ed. J.W. Stringer and D.L. Loftis, 128-136. General Technical Report SRS-24. Asheville NC: United States Department of Agriculture Forest Service Southern Research Station.

Patric, J.H. 1980. Effects of wood products harvest on forest soil and water relations. *Journal of Environmental Quality* 9(1):73-80. http://dx.doi.org/10.2134/jeq1980.00472425000900010018x

Reinhart, K.G., and Eschner, A.R. 1962. Effects on streamflow of four different forest practices in the Allegheny Mountains. *Journal of Geophysical Research* 67(6):2433-2445. http://dx.doi.org/10.1029/JZ067i006p02433

Reinhart, K.G., Eschner, A., and Trimble, G.R. Jr. 1963. *Effect on streamflow of four forest practices in the mountains of West Virginia*. Research Paper NE-1. Upper Darby, PA: United States Department of Agriculture Forest Service, Northeastern Forest Experiment Station.

APPENDIX C

KEY SOURCES OF INFORMATION ON FORESTRY BEST MANAGEMENT PRACTICES EFFECTIVENESS RESEARCH IN THE WEST

This appendix provides references, website addresses, and other information for key research on forest best management practice (BMP) effectiveness conducted in the western United States. For more detailed information on this subject, see Adams (2007); Adams and Ringer (1994); Cafferata, Coe, and Harris (2007); Ice et al. (2004); and Megahan and King, Rice et al., and Ice et al. in Ice and Stednick (2004).

Adams, P.W. 2007. Policy and management for headwater streams in the Pacific Northwest: Synthesis and reflection. *Forest Science* 53(2):104-118.

Adams, P.W., and Ringer, J.O. 1994. *The effects of timber harvesting and forest roads on water quality and quantity in the Pacific Northwest: Summary and annotated bibliography*. Prepared for the Oregon Forest Resources Institute. Corvallis, OR: Oregon State University, Forest Engineering Department.

Cafferata, P.H., Coe, D.B.R., and Harris, R.R. 2007. Water resource issues and solutions for forest roads in California. *Hydrological Science and Technology* 23(1-4):39-56.

Ice, G., Dent, L., Robben, J., Cafferata, P., Light, J., Sugden, B., and Cundy, T. 2004. Programs assessing implementation and effectiveness of state forest practice rules and BMPs in the West. *Water, Air, and Soil Pollution: Focus* 4:143-169. http://dx.doi.org/10.1023/B:WAFO.0000012821.68577.6b

Ice, G.G., and Stednick, J.D. (eds.) 2004. *A century of forest and wildland watershed lessons*. Bethesda, MD: Society of American Foresters.

CALIFORNIA

California Department of Forestry and Fire Protection (CAL FIRE) Watershed Research: In addition to supporting research at Caspar Creek, CAL FIRE has sponsored numerous field studies and monitoring efforts to assess the effectiveness and implementation of California's forest practice rules. A summary of some of these studies and key references can be found in Ice et al. (2004). An excellent summary of research on forest roads in California (sponsored by CAL FIRE and other work) is provided in Cafferata, Coe, and Harris (2007).

Ice, G., Dent, L., Robben, J., Cafferata, P., Light, J., Sugden, B., and Cundy, T. 2004. Programs assessing implementation and effectiveness of state forest practice rules and BMPs in the West. *Water, Air, and Soil Pollution: Focus* 4:143-169. http://dx.doi.org/10.1023/B:WAFO.0000012821.68577.6b

http://www.fire.ca.gov/CDFBOFDB/pdfs/IceEtALBMPPaper_pub.pdf

Cafferata, P.H., Coe, D.B.R., and Harris, R.R. 2007. Water resource issues and solutions for forest roads in California. *Hydrological Science and Technology* 23(1-4):39-56.

http://www.bof.fire.ca.gov/regulations/proposed_rule_packages/interagency_road_rules_2009/cafferata_et_al._2007_aih.pdf

California Department of Forestry and Fire Protection FORPRIEM Monitoring: This program provides data on the adequacy of implementation and effectiveness of the California forest practice rules specifically designed to protect water quality and riparian/aquatic habitats.

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_archived_documents/msg_archived_documents_/forpriem_proceduresmethods_091407.pdf

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_monitoring_reports/mcrfinal_report_2006_07_7b.pdf

Campbell Timberlands South Fork of Wages Creek Watershed Study: This is a study of the effectiveness of the California Forest Practices Act rules. It will identify sediment sources, determine changes in turbidity regimes following THP timber operations, and determine the effects of stream crossing reconstruction on changes in turbidity from above and below treatment sites.

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_supported_reports/2005_supported_reports/31_-_gma_2005_sf_wages_wy2004-2005.pdf

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_archived_documents/msg_archived_documents_/sfwages_effectivenessproposal_nov2004.pdf

Caspar Creek Watershed Study: This cooperative effort between the USDA Forest Service Pacific Southwest Research Station and California Department of Forestry and Fire Protection tests the effectiveness of California's forest practice rules, initially using a paired watershed approach. This is the only study with long-term experimental watersheds in the coast redwood vegetation type and is among the few throughout the United States with continuous records of streamflow and sediment that span nearly half a century.

http://www.fs.fed.us/psw/topics/water/caspar/

http://www.fs.fed.us/psw/topics/water/caspar/caspubs.shtml

Rice, R.M., Ziemer, R.R., and Lewis, J. 2004. Evaluating forest management effects on erosion, sediment, and runoff: Caspar Creek and northwestern California. In *A century of forest and wildland watershed lessons*, ed. G.G. Ice and J.D. Stednick, 223-238. Bethesda, MD: Society of American Foresters.

http://www.fs.fed.us/psw/publications/rice/riceSAF.pdf

Ziemer, R.R. (technical coordinator). 1998. *Proceedings of the conference on coastal watersheds: The Caspar Creek story*. General Technical Report PSW-GTR-168. Albany, CA: United States Department of Agriculture Forest Service, Pacific Southwest Research Station.

http://www.fs.fed.us/psw/publications/documents/gtr-168/gtr-168-pdfindex.html

Keppeler, E., Reid, L., and Lisle, T. 2009. Long-term patterns of hydrologic response after logging in a coastal redwood forest. In *The third interagency conference on research in the watersheds. Planning for an uncertain future—Monitoring, integration, and adaptation*, 265-271. US Geological Survey Scientific Investigations Report 2009-5049. Reston, VA: US Geological Survey

http://pubs.usgs.gov/sir/2009/5049/pdf/Keppeler.pdf

Garcia River Project: Trend and effectiveness monitoring of stream enhancement efforts in the Garcia River includes temperature responses and reductions to sediment loads.

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_supported_reports/2006_supported_reports/garciacdf2006finalreportcdf2_.pdf

http://www.treesfoundation.org/publications/article-367

Green Diamond Resource Company California Monitoring and Research: Green Diamond supports monitoring and research on fisheries as well as implementation of an Aquatic Habitat Conservation Plan.

http://www.greendiamond.com/responsible-forestry/research/california-aquatic-hcp/

http://www.greendiamond.com/responsible-forestry/research/fisheries/

Kings River Experimental Watershed (KREW): This USDA Forest Service study is looking at how prescribed fire and thinning can be used to reduce fire risks and how they affect hydrology, water quality, and aquatic communities.

http://www.fs.fed.us/psw/topics/water/kingsriver/

Sierra Nevada Adaptive Management Project (SNAMP): The SNAMP water team is researching water quality and quantity across treatment and control catchments before and after treatments that include thinning and prescribed fire in the central and southern Sierra Nevada. They are investigating impacts of strategic fuel treatments on water quantity and quality in SNAMP study areas.

http://snamp.cnr.berkeley.edu/

http://snamp.cnr.berkeley.edu/teams/water

Mendocino Redwood Company (MRC) and Humboldt Redwood Company (HRC) (formerly Pacific Lumber Company): Both MRC and HRC extensively monitor watersheds and aquatic communities. HRC has conducted surveys to identify sources of sediment observed in streams.

http://www.mrc.com/Monitoring-Aquatic.aspx

Sullivan, K. 2003. Variation in turbidity at the THP scale. Extended abstract. In *Conference on water quality monitoring – Spatial and temporal variability in forest water quality monitoring: Water quality research and regulations*, 16-17. December 1-2, 2003. Redding, CA.

Sierra Pacific Industries Watershed Research and Monitoring: Sierra Pacific Industries has conducted several studies on the effectiveness of the California Forest Practices Act rules. The Judd Creek Watershed Study and streamwater temperature response represent two examples.

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_archived_documents/msg_archived_documents_/judd_creek_final_prospectus_msg_maps.pdf

http://www.spi-ind.com/html/pdf_forests/WRPNo3.pdf

James, C. 2003. Stream temperature profiles and how they relate to logging prescriptions. Extended abstract. In *Conference on water quality monitoring – Spatial and temporal variability in forest water quality monitoring: Water quality research and regulations*, 11-14. December 1-2, 2003. Redding, CA.

Swanton Pacific Ranch (Little Creek) Watershed Study: The goal of this study by California Polytechnic State University is to evaluate the effectiveness of timber harvesting best management practices to prevent increases in stream suspended sediment export using single tree and group selection in the redwood/Douglas-fir region of California. A wildfire affected this research site in 2009.

http://www.spranch.org/research_watershed.ldml

http://www.bof.fire.ca.gov/board_committees/monitoring_study_group/msg_archived_documents/msg_archived_documents_/gaedeke_thesis_.pdf

Redwood National and State Parks: The impacts of road removal and watershed improvement work are actively monitored on former industrial timberlands that are part of Redwood National and State Parks. Additionally, several Redwood Creek watershed tributaries are continuously monitored for turbidity, suspended sediment concentration, flow, and water temperature. Channel adjustments following large storm events and extensive logging have been monitored for several decades, as have several biological indicators.

http://www.krisweb.com/biblio/biblio_redwood.htm

http://www.werc.usgs.gov/location.aspx?locationid=8

IDAHO

Idaho Quadrennial Audits and BMP Internal Audits: The Idaho Department of Environmental Quality is the lead agency for quadrennial audits of the forest practices program to evaluate BMP (Forest Practices Act rule) implementation and effectiveness. Between the quadrennial audits, an internal audit is conducted by the Idaho Department of Lands and the USDA Forest Service. Ice et al (2004) described the effectiveness component of these audits:

> "In recent years, evaluations of effectiveness have become a larger part of evaluation processes. In the 1996 audit (Zaroban et al. 1997), a simple yes/no evaluation was made on the question, 'Was sediment delivered to the stream from this forest practice?' No effort was made to quantify the amount of sediment or to evaluate the effects of the sediment on water quality and fish habitat. In the 1999 Forest Practices Water Quality Audit (Colla and DuPont 2000), the effort focused on habitat quality for bull trout in unharvested 'reference' and recently harvested sites" (p. 149).

Colla, J. and DuPont, J. 2000. *Forest practices water quality audit 1999*. Coeur d'Alene, ID: Idaho Department of State Lands.

Ice, G., Dent, L., Robben, J., Cafferata, P., Light, J., Sugden, B., and Cundy, T. 2004. Programs assessing implementation and effectiveness of state forest practice rules and BMPs in the West. *Water, Air, and Soil Pollution: Focus* 4:143-169. http://dx.doi.org/10.1023/B:WAFO.0000012821.68577.6b

Zaroban, D.W., Love, B., Colla, J., Lesch, G., Heimer, J., Lehner, J., Lukens, B., Poirier, S., Lee, B., and David, K. 1997. *Forest practices water quality audit 1996*. Boise, ID: Idaho Department of Health and Welfare, Division of Environmental Quality.

Colla and DuPont reported "this audit reaffirms what has been learned in past department and interagency audits. If the BMPs or rules are correctly implemented they appear to be effective at minimizing or avoiding impacts to affected resources."

The most recent quadrennial audit was in 2008 and the next audit will be in 2012. "The 2008 Audit had three components: an audit of rule compliance, a determination of shade and organic debris rule effectiveness, and an audit of special issues pertaining to stream crossings." Field staff assessed both compliance with and effective of the Forest Practices Act rules. "The Audit team observed a number of BMPs which were particularly effective in reducing soil erosion. We commend the use of slash mats and the surfacing of roads, particularly at approaches to water crossings."

Idaho Department of Environmental Quality (IDEQ). 2009. *Idaho 2008 interagency forest practices water quality audit: Rule compliance and stream crossing assessment*. Boise, ID: Department of Environmental Quality.

Mica Creek Watershed Study: This paired and nested watershed study is testing the effectiveness of the Idaho Forest Practices Act rules.

http://www.cnr.uidaho.edu/micacreek/

http://www.potlatchcorp.com/WaterQuality_Timberlands.aspx

Gravelle, J.A., Ice, G., Link, T.E., and Cook, D.L. 2009. Nutrient concentration dynamics in an Inland Pacific Northwest watershed before and after timber harvest. *Forest Ecology and Management* 257:1663-1675. http://dx.doi.org/10.1016/j.foreco.2009.01.017

Gravelle, J.A., and Link, T.E. 2007. Influence of timber harvesting on headwater peak stream temperatures in a northern Idaho watershed. *Forest Science* 53(2):189-205.

Hubbart, J.A., Link, T.E., Gravelle, J.A., and Elliot, W.J. 2007. Timber harvest impacts on water yield in the Continental/Maritime Hydroclimatic Region of the United States. *Forest Science* 53(2):169-180.

Karwan, D.L., Gravelle, J.A., and Hubbart, J.A. 2007. Effects of timber harvesting on suspended sediment loads in Mica Creek, Idaho. *Forest Science* 53(2):181-188.

MONTANA

Road Erosion Study: This study measured sediment from unsurfaced forest roads in western Montana. A regression with road slope, time since last road grading, roadbed gravel content, and precipitation explained 68% of variability in sediment yields. Minimizing road grading can reduce sediment yields from forest roads.

Sugden, B.D., and Woods, S.W. 2007. Sediment production from forest roads in western Montana. *Journal of the American Water Resources Association* 43(1):193-206. http://dx.doi.org/10.1111/j.1752-1688.2007.00016.x

Plum Creek Native Fish Habitat Conservation Plan: Monitoring associated with this Habitat Conservation Plan (HCP) includes stream temperature response to the applied riparian management zones.

http://www.fws.gov/montanafieldoffice/Endangered_Species/Habitat_Conservation_Plans/Plum_Creek_HCP/Tech-rpt_Wht-ppr/Intro.pdf

OREGON

Headwaters Research Cooperative (HRC): This research program was designed to "augment the body of science on headwater streams." Work funded by the HRC and other research on headwater streams is summarized in the April 2007 issue of *Forest Science*.

http://www.headwatersresearch.org/

HJ Andrews Experimental Forest: The HJ Andrews Experimental Forest provides sites for numerous watershed studies and was the location for important early research on landslides and forest roads.

http://andrewsforest.oregonstate.edu/

Luce and Black Road Study: A network of road segments was monitored to understand the factors leading to differences in sediment yields and runoff.

Luce, C.H. 2002. Hydrological processes and pathways affected by forest roads: What do we still need to learn? *Hydrological Processes* 16:2901-2904. http://dx.doi.org/10.1002/hyp.5061

Luce, C.H., and Black, T.A. 2001a. Effects of traffic and ditch maintenance on forest road sediment production. In *Proceedings of the seventh federal interagency sedimentation conference,* V67-V74. March 25-29, Reno, NV. Washington, DC: Federal Interagency Sedimentation Committee.

Luce, C.H., and Black, T.A. 2001b. Erosion over time from gravel-surfaced forest roads in western Oregon. In *Proceedings of the forest sedimentation conference*, 135-139. April 14-15, 1999, Tigard, OR. Northwest Forest Soils Council and Western Forestry and Conservation Association.

Luce, C.H., and Black, T.A. 2001c. Spatial and temporal patterns in erosion from forest roads. 165-178 in *Land use and watersheds: Human influence on hydrology and geomorphology in urban and forest areas – Water science and application 2*, ed. M.S. Wigmosta and S.J. Burges. Washington, DC: American Geophysical Union.

Oregon Department of Forestry (ODF): The Oregon Department of Forestry has maintained an active monitoring and research program to assess the effectiveness of the forest practice rules. Various ODF monitoring and technical reports are available.

http://www.oregon.gov/ODF/privateforests/monitoring.shtml

Examples

Robben, J., and Dent, L. 2002. *Best management practices compliance monitoring project: Final report*. Salem, OR: Oregon Department of Forestry.

Oregon Department of Forestry (ODF) and Oregon Department of Environmental Quality (ODEQ). 2002. *Sufficiency analysis: A statewide evaluation of FPA effectiveness in protecting water quality*. Salem, OR: Oregon Department of Forestry and Oregon Department of Environmental Quality.

Other Reports on the Website

The Oregon Forest Practices Act water protection rules: Scientific and policy considerations, December 1994

Cooperative stream temperature monitoring: Project completion report for 1994-1995, September 1999

Effectiveness of riparian management areas and hardwood conversions in maintaining stream temperature, March 1997

Storm impacts and landslides of 1996: Final report, June 1999

Compliance monitoring project: 1998 Pilot study results, November 1999

Compliance with fish passage and peak flow requirements at stream crossings pilot study results, March 2000

Aerial pesticide application monitoring final report, March 2000

Evaluation of the effectiveness of forest road best management practices to minimize stream sediment impacts – Final FY 96 Report to the Oregon Department Environmental Quality

Forest roads, drainage, and sediment delivery in the Kilchis River watershed, June 1997

Forest road sediment and drainage monitoring project report for private and state lands in western Oregon, February 1998

Harvest effects on riparian function and structure under current Oregon forest practice rules, July 2001

Shade conditions over forested streams in the Blue Mountain and Coast Range Georegions of Oregon, August 2001

Compliance with fish passage and peak flow requirements at stream crossings: Final study results, April 2002

Wet season road use monitoring project: Final report, June 2003

Compliance with leave tree and downed wood Forest Practices Act regulations: Results from a pilot study, February 2006

Oregon State University (OSU) College of Forestry: The Forest Engineering and Resource Management Department at OSU includes several faculty members who work on forest watershed issues. In addition to cooperating or conducting research as part of the Watersheds Research Cooperative, McDonald-Dunn Forest Road Study, and on Oregon State Department of Forestry research and monitoring, they have conducted or are involved in many other studies that assess BMP effectiveness. Key faculty include Dr. Paul Adams (http://oregonstate.edu/gradwater/paul-adams); Dr. Jeff McDonnell (http://www.cof.orst.edu/cof/fe/watershd/); Dr. Marvin Pyles (http://oregonstate.edu/gradwater/marvin-pyles); and Dr. Arne Skaugset (http://ferm.forestry.oregonstate.edu/facstaff/skaugset-arne). There are important cross-campus collaborations with staff in engineering, fisheries, and agriculture. There is also close collaboration with the **Cooperative Forest Ecosystem Research (CFER) Program** of the US Geological Survey (http://www.fsl.orst.edu/cfer/overview/index.html). The mission of CFER is to "… work closely with resource managers, researchers, and decision-makers to develop and convey information needed to successfully implement ecosystem-based management at forest stand and watershed scales, especially on lands dominated by young forests and fragmented by multiple ownership." Examples of papers from OSU faculty that address BMP effectiveness include the following.

Adams, P.W., and Taratoot, M. 2001. *Municipal water supplies from forest watersheds in Oregon: Fact book and catalog*. Portland, OR: Oregon Forest Resources Institute.

Hairston-Strang, A.B., and Adams, P.W. 1997. Oregon's streamside rules: Achieving public goals on private land. *Journal of Forestry* 95(7):14-18.

Pyles, M.R., and Skaugset, A.E. 1998. Landslides and forest practice regulation in Oregon. In *Environmental, groundwater and engineering geology: Applications from Oregon*, ed. S. Burns, 481-488. Association of Engineering Geologists Special Publication No. 11. Belmont, CA: Star Publishing Company.

Surfleet, C.G., Skaugset, A.E., and McDonnell, J.J. 2011. Uncertainty assessment of forest road modeling with the Distributed Hydrology Soil Vegetation Model (DHSVM). *Canadian Journal of Forest Research* 40:1397-1409. http://dx.doi.org/10.1139/X10-079

McDonald-Dunn Forest Road Study: A network of road segments was monitored to understand the factors leading to differences in sediment yields and runoff in a single watershed (Oak Creek). Additional research was conducted on forest roads in Oregon and California by Dr. Arne Skaugset of OSU and his students and colleagues.

http://water.oregonstate.edu/oakcreek/index.htm

Kibler, K. 2008. The influence of contemporary forest harvesting on summer stream temperatures in headwater streams of Hinkle Creek, Oregon. MS thesis. Oregon State University.

Royer, T. 2006. Scaling hydrologic impacts from road segments to a small watershed. MS thesis. Oregon State University.

Surfleet, C. 2008. Uncertainty in forest road hydrologic modeling and catchment scale assessment of forest road sediment yield. PhD dissertation. Oregon State University.

Surfleet, C., Skaugset, A., and McDonnell, J. 2010. Uncertainty assessment of forest road modeling using the Distributive Hydrology Soil Vegetation Model (DHSVM). *Canadian Journal of Forest Research* 40:1397–1409. http://dx.doi.org/10.1139/X10-079

Toman, E. 2007. Reducing sediment production from forest roads during wet-weather use. PhD dissertation. Oregon State University.

Toman E.M., and Skaugset, A.E. (in press). Reducing sediment production from forest roads during wet-weather hauling. Proceedings of the Tenth International Low Volume Roads Conference. *Journal of the Transportation Research Board*.

Watersheds Research Cooperative (Oregon State University): The Watersheds Research Cooperative has implemented a series of long-term paired watershed studies throughout Oregon that are evaluating the environmental effects on water and fish of contemporary forest management practices now in use on younger intensively managed forests. These studies are designed to provide credible scientific information on the impacts of contemporary forestry, as well as on opportunities to convey science findings through demonstration and public education. Key components include **Hinkle Creek**, the **Alsea Watershed Study Revisited**, the **Trask Watershed Study**, and **Stream Temperature Research**.

http://watershedsresearch.org/

Stednick, J.D. (ed.). 2008. *Hydrological and biological responses to forest practices: The Alsea Watershed Study*. New York: Springer.

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Entiat Experimental Forest: This paired watershed study began in 1957 and the original plans were to test the impact of harvesting and road construction the quality, quantity, and timing of runoff. A severe fire in 1970 changed the emphasis to an evaluation of wildfire impacts as well as watershed restoration. Research on the erosion impacts of alternative logging systems was also included (helicopter, logging over snow).

http://www.fs.fed.us/pnw/exforests/entiat/index.shtml

Klock, G.O. 1975. Impact of five post fire salvage logging systems on soils and vegetation. *Journal of Soil and Water Conservation* 30:78-81.

Woodsmith, R.D., Vache, K.B., McDonnell, J.J., Siebert, J., and Helvey, J.D. 2004. The Entiat Experimental Forest: A unique opportunity to examine hydrologic response to wildfire. In *Advancing the fundamentals sciences: Proceedings of the Forest Service National Earth Sciences Conference*, ed. M. Furnish, C. Clifton, and K. Ronnenberg, 205-216. PNW-GTR-689. Portland, OR: United States Department of Agriculture Forest Service, Pacific Research Station.

Forest Headwater Stream Riparian Ecosystem Management Studies (REMS): This buffer manipulation study was designed to determine the influence of alternative riparian management strategies on small non-fish streams in western Washington. A before-after-control-impact (BACI) study design looks at continuous and discontinuous buffers as well as no buffer options.

http://www.ecy.wa.gov/programs/eap/ForestPractices/REMS/index.html

Jackson et al. Headwater Research Study: This was a study of alternative riparian management schemes for headwater streams and impacts on key resources. Treatments tested included no stream-adjacent harvest, standard clearcut, full riparian buffer, and non-merchantable tree buffer. The latter was applied to only one site, while the other treatments were generally applied once or twice to four different treatment sites. This study showed how slash can affect water quality and channel conditions, as well as macroinvertebrate and amphibian communities. From the abstract to Jackson et al. (2007):

> "Logging slash immediately covered or buried clearcut channels with 0.5 to 2 meters of slash, increasing roughness and trapping fine sediments, and slash still dominated channel conditions in 2001 when fine sediment fractions remained elevated relative to reference streams. In buffered and reference streams, particle size distributions were almost unchanged. Buffer blowdown was extensive (33% to 64%); increased light stimulated streamside vegetation. In 1999, clearcut streams supported higher macroinvertebrate densities of collectors and shredders, likely due to increased detrital resources. Collector response persisted into 2001, and new responses included higher overall macroinvertebrate biomass in buffered streams. No macroinvertebrate groups declined significantly in the three summers after harvest. Clearcutting to stream channels appeared to have short-term negative effects on local giant salamander and tailed frog populations but not torrent salamanders."

Haggerty, S.M., Batzer, D.P., and Jackson, C.R. 2004. Macroinvertebrate response to logging in coastal headwater streams of Washington, U.S.A. *Canadian Journal of Fisheries and Aquatic Sciences* 61:529-537. http://dx.doi.org/10.1139/f04-014

Jackson, C., Batzer, D., Cross, S., Haggerty, S., and Sturm, C. 2007. Headwater streams and timber harvest: channel, macroinvertebrate, and amphibian response and recovery. *Forest Science* 53(2):356-370.

Jackson, C.R., and Strum, C.A. 2002. Woody debris and channel morphology in first- and second-order forested channels in Washington's Coast Ranges. *Water Resources Research* 38(9):1177-1190. http://dx.doi.org/10.1029/2001WR001138

Jackson, C.R., Sturm, C.A., and Ward, J.M. 2001. Timber harvest impacts on small headwater stream channels in the Coast Ranges of Washington. *Journal of the American Water Resources Association* 37(6):1533-1549. http://dx.doi.org/10.1111/j.1752-1688.2001.tb03658.x

Washington Cooperative Monitoring Evaluation and Research Committee (CMER): Cooperative research supports implementation and assessment of the Forest and Fish Agreement.

http://www.dnr.wa.gov/businesspermits/topics/fpadaptivemanagementprogram/pages/fp_cmer_active_projects.aspx

http://www.dnr.wa.gov/BusinessPermits/Topics/FPAdaptiveManagementProgram/Pages/fp_cmer_completed_projects.aspx

Washington Timber/Fish/Wildlife (TFW): This cooperative research program assessed the effectiveness of forest practices in Washington and was replaced by CMER.

http://www.dnr.wa.gov/BusinessPermits/Topics/FPAdaptiveManagementProgram/Pages/fp_am_tfw_publications.aspx

Examples of Key Publications

Rashin, E., Clishe, C., Loch, A., and Bell, J. 1999. *Effectiveness of forest road and timber harvest Best Management Practices with respect to sediment-related water quality impacts*. TFW-WQ6-99-001. Olympia, WA: Washington Department of Ecology, Timber, Fish, Wildlife Program.

Rashin, E., and Graber, C. 1993. *Effectiveness of BMPs for aerial application of forest pesticides*. TFW-WQ1-93-001. Olympia, WA: Washington Department of Ecology, Timber, Fish, Wildlife Program.

Another Washington Department of Natural Resources (WDNR) website that provides Timber/Fish/Wildlife and WDNR research reports (including many studies by Dr. Jeff Cederholm on the Olympic Peninsula) is http://www.dnr.wa.gov/ResearchScience/Pages/PubResearch.aspx

Washington Intensively Monitored Watersheds (IMW): A series of intensively monitored watersheds is being established in Washington for the purpose of better understanding how salmon and trout respond to current approaches for restoring habitats.

http://www.ecy.wa.gov/programs/eap/imw/index.html

Weyerhaeuser Deschutes Watershed Study: Thirty years of monitoring of turbidity in the Deschutes Watershed of Washington showed "dramatic declines in turbidity even with continued active forest management." The authors concluded that "…increased attention to reducing sediment production from roads and minimizing the amount of road runoff reaching stream channels has been the primary cause of the declining turbidity levels observed in this study."

Reiter, M., Heffner, J.T., Beech, S., Turner, T., and Bilby, R.E. 2009. Temporal and spatial patterns over 30 years in a managed forest of western Washington. *Journal of the American Water Resources Association* 45(3):793-808. http://dx.doi.org/10.1111/j.1752-1688.2009.00323.x