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Research Gaps Related to Forest Management and Stream Sediment in the United States

Christopher J. Anderson · B. Graeme Lockaby

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Abstract Water quality from forested landscapes tends to be very high but can deteriorate during and after silvicultural activities. Practices such as forest harvesting, site preparation, road construction/use, and stream crossings have been shown to contribute sediment, nutrients, and other pollutants to adjacent streams. Although advances in forest management accompanied with Best Management Practices (BMPs) have been very effective at reducing water quality impacts from forest operations, projected increases in demand for forest products may result in unintended environmental degradation. Through a review of the pertinent literature, we identified several research gaps related to water yield, aquatic habitat, sediment source and delivery, and BMP effectiveness that should be addressed for streams in the United States to better understand and address the environmental ramifications of current and future levels of timber production. We explored the current understanding of these topics based on relevant literature and the possible implications of increased demand for forest products in the United States.

Keywords Best management practices · Forest management · Sediment · Water quality · Watershed management

Introduction

Research and monitoring have shown that water coming from forested landscapes tends to be of very high quality (Stednick and others 2004). This is particularly the case when compared to other human dominated landscapes such as agriculture, urban, and industrial (Ice and others 1997; Shepard and others 2004). Based on the U.S. Environmental Protection Agency National Water Quality Inventory 2002 Report (USEPA 2007), forestry was not ranked among the leading land uses causing significant pollution to the Nation's rivers and streams despite the fact that forests cover approximately one-third of the U.S. and the U.S. is the leading producer of wood products in the world (FAO 2009). High water quality from forested lands is partially attributed to a variety of physical and biogeochemical processes that filter and improve water as it passes through a watershed. During forest management, water quality can be maintained through state forest practice statutes (e.g., California, Oregon, and Washington) and the implementation of forestry Best Management Practice (BMP) programs and guidelines that are available in all 50 states (Schilling 2009).

While current forestry practices (harvesting, site preparation, regeneration) in the U.S. generally result in modest water quality impacts (increased nutrient concentrations, sediment loads, temperature, turbidity, etc.), a wide variation of impact severity has been reported (Sun and others 2004; Aust and Blinn 2004; Megahan and King 2004). This variation can be partially attributed to the range of harvesting practices, geographical differences (including forest type, topography, climate, soils, etc.), management intensities, and inconsistent use of BMPs (Binkley and others 2004; Ice and Stednick 2004). Current impacts to water quality are sometimes inappropriately characterized by the results of past studies that examined management practices which are either outdated or excessive today (e.g., minimal or no BMP use). Oregon, for example, adopted the first state forest practices act in 1971 specifically designed

C. J. Anderson (✉) · B. G. Lockaby
School of Forestry and Wildlife Sciences, Auburn University, 3301 Forestry and Wildlife Building, Auburn, AL 36849, USA
e-mail: andercj@auburn.edu

to protect water quality and fish habitat. But paired watershed information has been limited to historic studies such as the Alsea Watershed Study conducted from 1959 to 1973 (Beschta and Jackson 2008). Only after 30 years has the Hinkle Creek Watershed Study been initiated to look at water quality impacts from more contemporary practices, such as the regular implementation of streamside management zones (SMZs) where harvesting is limited or excluded.

Different phases of forest management can affect water quality with harvesting the most frequently cited activity. A variety of hydrologic effects have been linked to harvesting but the most consistently reported effect is increased water yield (Neary and Hornbeck 1994; Stednick 1996; Williams and others 1999; Grace 2005; Hubbart and others 2007). While most research from forest operations has estimated over land sediment sources, in-channel sources can become significant where water yields are altered, especially after intense rainfall (Gomi and others 2005). Other land use research has shown that increased water yields can scour stream channels and mobilize bedload, particularly where there has been substantial stream aggradation in the past (Ursic and Douglass 1979; Nelson and Booth 2002; Beasley and others 2004).

During and after timber harvest, major water quality concerns involve soil disturbance, sediment and nutrient runoff, sedimentation, and changes to stream temperatures. Cumulatively, elevated sediment levels can be generated from a variety of potential sources such as soil eroded from the harvest area, skid trails, roads, and remobilization of previously eroded soil (Croke and Hairsine 2006). While numerous publications have reported elevated soil erosion as a result of forestry practices (Binkley and Brown 1993; Shepard and others 2004; Grace 2005), less is known about how and how much of this material is transported to the stream or the relative importance of different sources (e.g., harvest areas and roads) (Croke and Hairsine 2006). Following harvest, there are a variety of management activities (prescribed burning, herbiciding) and climatic conditions that may contribute to sediment yield over time. Sites are often managed to enhance future tree growth prior to planting and these practices also have the potential to increase sediment/nutrient runoff and impair stream quality (Wynn and others 2000). In the West, pre- and post-fire management can impair water quality. Post-fire management normally emphasizes soil conservation to enhance the recovery effort and maintain water quality (Beschta and others 2004). Post-fire logging can delay forest recovery through soil compaction, erosion, the removal of shade and organic sources, and increased runoff (Karr and others 2004). Major precipitation events also cause tremendous sediment flux (Swank and others 2001; McBroom and others 2008a). Determining the long-term significance of large storm events in relation to forestry operations is problematic because most studies have assessed this phenomena in the short-term (<4 years). The timing of forest operations, climatic events, and research studies poses a significant challenge to those seeking to develop guidelines that minimize water quality impacts while not being overly restrictive.

Best Management Practices are designed to reduce and mitigate water quality impacts that can arise from forestry activities. Best Management Practice programs have evolved since their adoption in response to the 1972 Federal Water Pollution Control Act (Clean Water Act). Both the implementation of state BMPs and their effectiveness are the subjects of recurring investigations. Surveys find that current BMP compliance is generally high (Schilling 2009) and effective at reducing impacts (Ice 2004; Wynn and others 2000). The rate of BMP compliance and effectiveness are notable because these practices are voluntary in most states and water quality from managed forests has improved over time. Long-term water quality data have demonstrated the efficacy of improved forest management techniques. In western Washington, Reiter and others (2009) found that water quality improved at four locations along the Deschutes River system between 1975 and 2005. These trends were observed in small ($\leq$3.0 km^2) and large (150 km^2) catchments and occurred even though forest operations remained active during that time period.

The efficacy of current forestry practices to protect water quality may be tested in the future as management pressure on forests is expected to increase over the next half-century. The United Nations Food and Agricultural Organization (FAO) 2009 State of the World's Forests reported several worldwide trends that are expected to increase the demand for forest products over the next several decades (FAO 2009). These trends include population growth, long-term economic growth (especially rapidly developing economies such as China), and changes in energy policies that increasingly emphasize wood use. These global drivers will influence forest management in the U.S. to varying degrees but overall are expected to increase the demand for major wood products (industrial roundwood, sawnwood, wood-based panels, paper/paperboard, and biofuels). Increased demand for forest products will likely lead to more intensive and extensive management in the form of increased harvest removals, more frequent entry into stands, harvest of larger areas, concentrated production over fewer acres, and an increase of watersheds disturbed at any given time. These changes, however, may vary by region. In the West, where forestlands are predominantly in public ownership, pressure to increase timber production may not be as severe. These forests are subject to institutional policies and increasingly being managed for other non-timber related services. In the

East, where private forest ownership dominates, the pressure to increase productivity may be more acute and potentially increase related environmental impacts. In the Southeast, where forests are increasingly converted to urban land (Wear and Greis 2002), demand on remaining timberlands may become particularly high. Through their model projections, Prestemon and Abt (2002) predicted that the industrial wood output in the South may increase by more than 50 percent between 1995 and 2040.

To assess the potential implications for increased timber production on stream sediment yield, we reviewed pertinent literature to identify important related research gaps. Our review focused on stream sediment which has been the dominant water quality concern associated with forest management, but acknowledge other water quality concerns (e.g., nutrient and pesticide runoff) associated with forestry (Neary and others 1993; Neary and Michael 1996; McBroom and others 2008b). Our objective was not to provide a comprehensive review of forest management and water quality as this has been well documented (Binkley and Brown 1993; Ice and Stednick 2004; Aust and Blinn 2004; Jackson and others 2004; Gomi and others 2005; Grace 2005; Moore and Wondzell 2005). Instead, based on the peer reviewed literature, we identified several important research gaps related to forest operations and sedimentation of streams that may become critical if the demand for forest products increases in the future. We evaluated how these research gaps may become important with increasing timber demand, and provided suggestions and identified examples of research that have begun to address these gaps.

Research Gaps

We identified four categories of research gaps related to forest operations and sedimentation of streams: timber harvesting effects on water yield and water quality, temporal and spatial scale of sediment delivery, sediment/water yield from roads, and assessing the effectiveness of Best Management Practices. For each category, we provide relevant research and explain important research gaps. A summary of our findings is provided in Table 1.

Timber Harvesting, Water Yield, and Water Quality

Most of the literature regarding forest management and water quality has focused on the effects of timber harvesting. The most common effect of decreased forest cover is increased water yield due to the decrease in evapotranspiration and canopy interception of rain (Stednick 1996). Soil compaction and decreased water infiltration caused by mechanized equipment have also been cited as reasons for higher yields (Aust and Blinn 2004). Water yield changes often vary considerably depending upon physiographic region and harvest intensity. In a review of 10 forest harvest studies in the southern U.S., Grace (2005) found water yields increased anywhere between 40 and 210 mm year^{-1} the first year after harvest. In their review of the Pacific Northwest (PNW), Moore and Wondzell (2005) reported that a relationship between post-harvest water yield and harvest intensity was sometimes undetectable (in coastal regions) or highly variable (in snow-dominated regions). Looking at coastal PNW studies, Grant and others (2008) found different relations between peak flow increase and harvest intensity for rain-dominated and transient-snow regions (where rain on snow conditions are common). While water yield often increases immediately after harvest, it also tends to decrease rapidly in subsequent years. Sun and others (2004) reported that as regeneration occurs after harvest, increases in water yield can be expected to decline logarithmically each subsequent year. Grace (2005) also reported marked declines in water yield from ten reviewed southern studies after initial post-harvest increases.

While increased water yield by itself is not considered a serious impact (and in some instances may be beneficial to downstream users and ecosystems; Harr 1983), it can lead to related problems such as sediment movement and nutrient runoff. There is evidence that increased water yields and peak flows can erode existing stream channels and significantly increase sediment loads (Thornton and others 2000; Schoenholtz 2004). In the Southeast U.S., where streams often contain a substantial legacy bedload from massive agricultural conversion over 100 years ago, increased water yield can re-suspend sediment already in the stream channel (Trimble 1974; Jackson and others 2005). Other regions throughout the U.S. also contain highly aggraded streams and rivers with substantial amounts of legacy sediments (Knox 1987; Peck and others 2007; Walter and Merritts 2008). For these streams, when sediment concentrations increase in response to forestry operations, the prevalent sediment sources may be uncertain. The use of BMPs to reduce over land flow of sediments may only have a marginal effect on suspended sediment loads if most material originates from within the channel and is being moved as a result of higher water yields.

Future research is needed to separate the contributions from the various potential suspended sediment sources. Sediment tracing techniques such as isotopic (Papanicolaou and others 2003) and radionuclide tracers (e.g., Cs^{137}, Wallbrink and others 2002) have been used successfully in forestry and elsewhere to track the origin of sediment in a watershed or management activity. Radionuclides can be particularly useful in forestry applications because they

Table 1 Research gaps identified and suggested approaches (with examples) for mitigating sediment production and delivery from forest management

Research gaps	Suggested research approaches (cited example study and/or information source)
Determining stream sediment from in-channel vs. over land sources	Increased utilization of nuclide and isotopic tracers within existing and future watershed studies (Wallbrink and Croke 2002)
The influence of short-term perturbations on the long-term health of aquatic communities	Extended durations of watershed research and long term monitoring of aquatic communities. Meta-analyses of existing data where available
Influence of watershed size on sediment yield	Additional watershed studies that are explicitly designed to evaluate sediment yield relative to watershed size (McBroom and others 2008a)
Cumulative watershed effects (CWEs) of forest operations on sediment yield	Sediment tracing and modeling efforts that explain the temporal/spatial variability of forest management activities and support CWE model development (MacDonald and others 2002)
Tracking sediment produced from roads and its delivery to streams	Research designed to track both sediment production and delivery to streams (Miller and others 1985; Bilby and others 1989; Walling 2005).
The influence of improved mountain road designs and construction on mass soil losses	Monitoring and meta-analyses of current vs. past frequencies of mass erosion events (Gucinski and others 2001)
The merit of road abandonment vs. restoration	Research comparing total sediment yield from abandoned and restored road scenarios (McCaffery and others 2007)
Optimizing BMP applications for sediment reduction	Research designed to identify optimal BMP applications and support optimization models (Madej and others 2006)
Quantifying the effectiveness of different BMPs	Research designed to better explain mechanisms and quantify the amount of sediment retained by different BMPs (e.g., White and others 2007)

tend to be most active in surface soils and less so at the subsurface (Walling 2005). Several noteworthy studies involving sediment tracing in forestry applications have emanated from Australia using Cs^{137} methods (Wallbrink and Croke 2002; Wallbrink and others 2002). Wallbrink and others (2002) effectively tracked sediment movement and storage among different management elements of a forestry operation (i.e, the general harvest area, skid trails, filter strips). Statistical tools such as Aikaike's Information Criterion (Loupe and others 2009) and multivariate approaches (Hartano and others 2003; Zeng and Rasmussen 2005) have been increasingly used with existing data to select appropriate model variables and discern key factors related to water quality. Incorporating tracer studies and effective analyses in current and future forestry studies could greatly improve understanding of in-channel and other potential sediment sources.

Temporal and Spatial Scale of Sediment Delivery

Although soil erosion and stream sediment have been a primary focus of forestry related impact studies, there are still questions regarding how these processes vary over space and time. Temporal variability can stem from a wide range of climatic conditions that may influence and sometimes overwhelm study results. Several reports have identified major storms as the primary factor responsible for sediment movement (Swank and others 2001; McBroom and others 2003; Beasley and others 2004) which may be difficult to account for during short-term studies. Some short-term studies (<4 years) have shown virtually no water quality impacts associated with forest operations when the study occurs during a period without a large storm event (see Carroll and others 2004). On the contrary, short-term studies that coincide with major storm events may overestimate the impact of forest operations on water quality. Long-term forest watershed monitoring and research peaked in the 1960s but has declined as funding for such projects has been reduced (Stednick 1996). While watershed monitoring will likely never reach these levels again, maintaining long-term efforts would help put climatic variability and its effect on sediment yield in perspective. Accounting for temporal variability is important as streams are normally dynamic systems that are often subject to extreme weather events (Blackburn and others 1986; McBroom and others 2003).

Important to understanding the temporal variability of sediment movement is how it affects aquatic organisms (Henley and others 2000). In some cases, the impact may be negligible because when forestry or storm related water degradation occurs, it is a short-term phenomenon. Although little is known about the overall influence of short-term water quality impairment on aquatic communities, some investigations have shown that BMPs effectively protect aquatic habitats. In a 3-year investigation, Vowell and Frydenborg (2004) used a multimetric stream assessment (Stream Condition Index) on five harvested watersheds throughout north Florida. They found that where BMPs were implemented, no impacts to stream habitat could be attributed to forest operations. Excess sediments from forest operations may cause stream aggradation and burial of stream-bottom habitat. Megahan and King (2004) point out that more research is needed to define allowable impacts from forest operations, but reported that an increase of about 100 percent in background sediment load is generally needed to cause measurable changes in channel aggradations. Furthermore, forest operations are very different today than they were in the past decades and long-term studies that capture the full range of normal precipitation events while accounting for current operational practices are needed to adequately assess the current impact on water quality.

Water quality standards intended to protect aquatic ecosystems may be unable to account for highly variable conditions that occur naturally or because of management (Ice 2004). There is even evidence to suggest that some level of disturbance may benefit certain ecosystems. Wilzbach and others (2005) found that trout biomass increased in a stream where alder in the riparian corridor was experimentally cut to increase incident radiation. A meta-analysis by Mellina and Hinch (2007) of 25 studies with streamside clearcut logging found that salmonid density and biomass generally increased following logging except where large wood was removed from the streams. Miller and Benda (2000) noted that landslides that overwhelm streams with sediment can have long-term benefits by creating off-channel habitat for fish. Additional studies that consider the broader, long-term effects (both positive and negative) of short-term perturbations on aquatic communities are encouraged.

Similarly, watershed scale and stream order are important spatial factors to consider when examining the changes caused by forestry operations. At the headwaters, intermittent and ephemeral streams may be highly variable and much more responsive to surrounding conditions than higher order streams. In east Texas, McBroom and others (2008a) evaluated 13 watersheds (9 small [<3 ha] and 4 large [>70 ha]) and compared post-harvest data collected in 2002 (using BMPs) to results from the same watersheds after a 1981 harvest where land disturbance was more intense and BMPs were not utilized. For the smaller watersheds, average sediment loss following the 2002 harvest was lower than that observed in the 1980s although estimates were highly variable. The watershed with the greatest 1-year sediment loss (540 kg ha^{-1}) following the 2002 harvest was only one-fifth the average loss reported on sheared watersheds (2937 kg ha^{-1}) in 1981 (Blackburn and others 1986; McBroom and others 2008a). Unlike many of the smaller watersheds in the study, larger watersheds showed no appreciable changes in stormflow and sediment load between pre- and post-harvest years. The authors credited contemporary BMPs (e.g., SMZs) for providing rainfall interception, higher rates of evapotranspiration, and protecting stream channels. In a review of literature from the PNW, Grant and others (2008) also reported that smaller watersheds (<10 km^2) have greater increases in peak flow after harvest compared to larger watersheds. We suggest that other watershed research and management consider variability in watershed size and study scale when designing studies on responses to forest operations.

The variability of activities associated with forest management can make it very difficult to ascertain the contribution of individual activities to sediment yield. Cumulative watershed effects (CWEs) occur from the combined impacts of forestry activities over space and time (Reid 1993; MacDonald and others 2002). For instance, the impact of various activities on stream sediment delivery may change over time with some being immediate while others lag years after completion. This is further complicated by the spatial proximity of activities within the watershed. Recognizing and understanding CWEs are important for managing the potential impacts caused by forest operations and has lead to a range of CWE assessment methods such as the Equivalent Road Area procedure (Berg and others 1996). Given the complexity of CWEs, effective models are needed to account for the temporal and spatial variability inherent to sediment delivery. Model developers trying to account for cumulative impacts often do not have the data needed to predict site-level changes in sediment production (MacDonald and others 2002). Research that improves regional understanding of sediment sources, timing, and delivery will ultimately improve efforts to identify, assess, and model CWEs.

Sediment/Water Yield from Roads

Forest roads are usually necessary to remove timber from the forest but have been cited as a primary source of pollution related to forestry operations (Bilby and others 1989; Swank and others 2001). The amount of sediment yield in streams has been shown to be proportional to the relative density of roads in the watershed and inversely proportional to the time since they were built (Schoenholtz 2004). However, perhaps just as important is where and how the roads are built. In a northern hardwood forest in Ontario, Kreutzweiser and Capell (2001) found that watersheds with road improvement activities elicited the greatest increase in stream bedload when compared to a variety of harvest intensities (up to 85% canopy removal). Reviewing studies from the northern Rocky Mountains, Megahan and King (2004) found that forest harvests often had minor impacts on streams and identified roads as the major source of sediment associated with forestry operations. In the Southeast U.S., roads often need to traverse through wetlands where sediment issues can shift from over land flow to maintaining low flow velocities (Rummer 2004).

Determining road generated sediment yield from other sources (harvest sites, landing areas) can be difficult because sediment is often generated concurrently (Moore and Wondzell 2005; Grant and others 2008). Literature from the PNW transient snow zone showed that the maximum percentage increase in peak flow consistently occurred in catchments with road areas >2% regardless of harvest intensities (Grant and others 2008). At the Mica Creek Experimental Watershed in northern Idaho, Hubbart and others (2007) used long-term stream flow data (1991–2005) to separate hydrologic impacts caused by harvesting intensity and roads. In one catchment (139 ha), they found that water yield increased by 68 mm year^{-1} after road construction but then increased by 270 mm year^{-1} following a 50% clearcut. Another catchment showed no significant change in water yield following road installation. Extensive research in the southern U.S. has shown that forest roads can increase water yield and soil loss over a variety of physiographic regions but often sediment comes from just a small portion of the road network (Swift 1984; Swift 1988; Arthur and others 1998; Swank and others 2001; Rice and Lewis 1991; Grace 2005). This may be especially true where landslides or gully erosion occurs.

Although research relating forest roads and water quality has been extensive, there are knowledge gaps that should be addressed. One is the connection between soil erosion (a commonly measured parameter related to sediment loading) and water quality. Grace (2005) points out that there is substantial literature looking at erosion rates related to forestry roads but not enough research has made the direct connection between erosion rates and sediment delivery to streams. In southwestern Washington, Bilby and others (1989) examined sediment generated from road surfaces and tracked it into first and second order streams before being transported to larger streams. The fine sediment material (most < 0.004 mm) quickly flushed through streams while coarser particles were disproportionately retained in streams. In the Ouachita Mountains of Arkansas, Miller and others (1985) traced 70% of the total sediment delivered from a forestry operation back to roads however the estimated amount of sediment delivered from roads (0.09 t ha^{-1} year^{-1}) was far less than the soil loss estimated from the roads (55 t ha^{-1} year^{-1}). The literature clearly shows that roads result in soil movement but it is often uncertain how much is delivered to streams. Further research should take the approaches of Bilby and others (1989) and Miller and others (1985) to track the fate of sediments mobilized from roads.

In regions with the steepest terrain, research is needed to address roadway effects on mass soil losses and the effect of decommissioned, abandoned, or restored roadways. On this terrain, roads have been shown to elicit mass erosion (i.e., landslides). Gucinski and others (2001) reported that forest road locations, design, construction, and engineering have all improved over the past 30 years, but few studies have quantified the improvements made to lowering mass erosion rates. Likewise, few studies have examined the fate of roads as sediment producers when they are restored or abandoned. Preliminary research has shown that road removal may be a short-term sediment source but over the long-term it can reduce sediment delivery and landslide risks (Switalski and others 2004). McCaffery and others (2007) reported that watersheds with decommissioned roads in the Flathead National Forest, Montana had streams with less fine-sediment than watersheds with active roads and emphasized the value of vegetation on abandoned roads to improve stream habitat. Studies such as these that evaluate alternative management plans for abandoned roads may be particularly important in public forests where silviculture activities are diminishing.

Assessing the Effectiveness of Best Management Practices

Tremendous work has gone into the development of forestry BMPs and research has shown they are highly effective at minimizing the impacts to soil and water quality caused by forestry operations. This has been reported in several reviews covering broad geographical areas (Brown and Binkley 1994; Vowell 2001; Ice 2004; Sun and others 2004; Grace 2005; Schilling and others 2007). Best Management Practices such as SMZs, vegetated filter strips, or brush barriers are intended to separate streams from forest operations. Other BMPs include planning or procedural measures which reduce the footprint of mechanized equipment and roads, maintain soil cover such as understory vegetation or organic matter, and stabilize exposed and disturbed soils. Specific BMPs have been developed to minimize forest road and skid trail impacts including measures to disperse roadway runoff, and separate forestry activities from streams. Although it is clear that BMPs (when properly installed) maintain water quality, we are just beginning to quantify the effectiveness of different practices (Moore and Wondzell 2005).

More research is needed to provide empirical relationships between different BMPs used and pollutant reductions. This information would support modeling efforts and focus BMP requirements and expenditures where they are needed most. Other land-uses, such as agriculture, are exploring optimization methods to simultaneously achieve economic and environmental goals (Osei and others 2003; Veith and others 2004). Xiao-Yue and others (2004) combined a heuristic optimization technique with a watershed model to generate a least-cost set of solutions for meeting agricultural water quality goals. Veith and others

(2004) determined the cost of sediment reduction was reduced from \$42 to \$36 per kg sediment ha^{-1} by optimizing the location of BMPs instead of uniformly applying them. Optimization methods have been used for forest road removal and sediment reduction decisions (Madej and others 2006; Thompson and others 2010) but could be developed for other forestry applications.

Efforts to quantify BMP effectiveness would help identify areas where measures are needed for water protection, but also where measures may be excessive. Kreutzweiser and Capell (2001) found minimal impacts to headwater streams without buffers in Ontario for selective forest harvests with up to 50 percent canopy removal. They suggested that in some regions, SMZs may not be necessary to maintain water quality if harvesting intensity remains low to moderate. Studies by Arthur and others (1998) in the Cumberland Plateau of eastern Kentucky and Beasley and Granillo (1982) in the Gulf Coastal Plain of Arkansas showed that in worst case scenarios where forests were clear-cut without BMPs, the resulting post-harvest export was less than 1.0 and 1.5 t ha^{-1}, respectively. While this is a considerable amount, it is much less than often reported for other intensive, non-forestry land uses (Grace 2005). Although SMZs may not always be necessary for sediment control, they also help stabilize stream banks, maintain water temperatures, and provide a source of wood and fine organic matter to streams. Managers would benefit from greater predictive abilities regarding sediment control provided by various BMPs and the other contributions they provide to water quality.

Just as there is uncertainty regarding the extent of BMP effectiveness, the actual mechanisms associated with BMPs and water quality improvements are often unclear. For instance, SMZs are commonly credited for mitigating water quality during forestry operations but how the protection is afforded is often unclear (e.g., does it capture over land flow of sediment?, does it reduce stream channel scouring?, both?). Understanding the mechanisms that contribute to BMP effectiveness would allow managers to better predict sediment retention and maximize cost effectiveness and application. Future research should be directed toward describing the mechanisms of sediment retention associated with BMPs. For instance, a study by Rivenbark and Jackson (2004) looked at the specific causes of SMZ failures and successes and found that 50% of SMZ breakthroughs (i.e. locations where sediment had been transported well into or through the SMZ) occurred where some type of water convergence zone (swale, gully, etc) intersected with the SMZ. Twenty-five percent of the breakthroughs were linked to concentrated runoff from trails and roads. Exposed soil within the SMZ, particularly near steep slopes, was also a factor associated with breakthroughs in many cases.

Better understanding of SMZ mechanisms could also shed light on the uncertainty regarding necessary buffer width. Recent research in Virginia (Lakel and others 2006; Lakel 2008) looked at the effectiveness of 7.6-, 15.2-, and 30.5-m wide buffers on 30% slopes in the Virginia Piedmont to retain sediment. It was concluded that the narrower SMZ (7.6 m) and a thinned 15.2-m SMZ were just as effective as wider treatments at retaining sediment after timber harvest and site preparation. The authors suggested that this differential response may be due to the greater proliferation of understory (i.e. roughness) driven by increased light availability (Lakel and others 2006). There is increasing interest in SMZ thinning as a management tool to enhance SMZ effectiveness. Research in Georgia (White and others 2007) has demonstrated that SMZs and filter strips provide multiple functions by removing smaller sediment aggregates (<20 μm) through infiltration while removing larger aggregates through filtration. Knowing potential sediment aggregate sizes on site and how they can be retained by SMZs may lead to more empirically-based decisions on necessary SMZ widths and conditions.

Predictive Models and Future Applications

There has been a tremendous amount of research devoted to forest management and its implications for stream water quality. This work has shaped policy and management guidelines so that forest lands (managed or not) continue to yield high water quality. Although forestry operations have the potential to degrade receiving waters, there is overwhelming evidence that these impacts are minimized through proper implementation of BMPs. Nevertheless, there are important research questions that should be answered regarding the influence of water yield, effects on downstream aquatic communities, and resolving the ratio of soil loss to sediment delivery and BMP effectiveness (Table 1). Through our review, we have identified some of the key research gaps that remain and examples of supporting research and research approaches that address these gaps. Better understanding of these issues provides a basis for more effective forest management by targeting problematic areas or processes related to water quality. Providing this guidance will become more pertinent if pressure increases to maximize future timber productivity.

An important advancement in watershed science underlying future research is the increased use of predictive models. With rapid advances in microcomputing, watershed models will increasingly be generated to guide land management decisions (Neary and others 2009). Models can be considered a synthesis of our understanding of how a system interacts and consequently the capability of a model is only as good as the information used to develop it

(Mitsch and Jørgensen 2003). While models have traditionally been used to explain and predict systems, they can also be tools for new understanding and are increasingly used for research applications. Some of the most appropriate research using models will be discerning the influence of interacting components in the watershed and their role in water and sediment yield. Models can explore land use effects that cannot be adequately researched using watershed experiments or other field methods. They also can account for a wide array of temporal (e.g., climate) or geographic conditions as opposed to watershed studies that operate at a specific location over short time intervals. For instance, Ziemer and others (1991) used Monte Carlo simulations to evaluate the rate and spatial placement of forest cuts in hypothetical 10,000-ha, fifth-order watersheds over a 200 year time scale. They found important differences between treatments manifested in the first 100 years and that dispersing cuts throughout the watershed versus progressing upstream did not significantly reduce cumulative effects. Obviously, these types of research questions cannot be addressed using field studies.

As modeling efforts increase in complexity, there will be increased emphasis to develop and utilize physical based models to explain and support management decisions. Forest watershed models have become increasingly sophisticated and will be used increasingly to guide future forest management particularly in the face of climate change and population growth (Neary and others 2009). Current and future models that best predict sediment yield are those which analyze for slope stability (both roads and cutovers) before and after harvest. Modeling does have limitations though, including poor performance during extreme climatic events which may be very important for sediment movement but have very different hydrologic controls than regular storm events (Eisenbies and others 2007). Models have been suggested to provide guidance on complex issues such as evaluating cumulative watershed effects caused by timber harvesting and its risk to ecosystem values in the Redwood region of northern California (Standiford and Arcilla 2001). Field research such as those reviewed here will be necessary to refine, calibrate, and validate existing watershed models (Arp and Yin 1992; Rhee and others 2004; Borah and others 2006) so that they account for not just soil erosion but sediment delivery to streams. Beschta (1998) identified the need for measured precipitation and subsurface flow patterns across varied landscapes as research gaps in the PNW to improve understanding of landslide mechanics, subsurface models, and peakflow estimates. Models are generally well-suited to predict surface erosion but often provide discrepancies between predicted and actual sediment yields (Ketheson and others 1999). Common watershed models such as WEPP and SWAT have been advanced to estimate nonpoint source pollution loading from agricultural lands but these models need to be further modified for better application to forest management (Sun and others 2004).

Successful research which addresses the knowledge gaps identified in this paper can increase the resolution of existing watershed models. There is an increasing tendency to only use models to explain many of the complexities associated with land use and environmental impacts, however we agree with Stednick and others (2004) that modeling efforts need to be complimented with field research to adequately address the prevailing forestry management questions (what are the sediment sources?, is it really harmful to downstream habitats?, how much sediment did the BMP retain?) and confirm model outputs. These efforts may require region- and management-specific efforts that represent a range of conditions found across various physiographic regions.

The efficacy of BMPs to maintain water quality has already been strongly supported by a substantial wealth of forested watershed research (Ice and Stednick 2004). This is important because it is expected that the demand for forest products will increase substantially over the next 40 years (FAO 2009). By better understanding how forestry impacts (e.g., sediment yield) occur over space and time, appropriate strategies can be developed to mitigate increased management intensity. While implementation of forestry BMPs is capable of minimizing impacts and maintaining water quality, there is often a perception among many NGOs and agencies that voluntary BMPs equate to unregulated activity. If demand for forest products increases, effective BMP implementation will be imperative for maintaining the important strides made by the forest industry and alleviate future concerns and scrutiny by the public.

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