SEDIMENT ASSOCIATED WITH FOREST OPERATIONS IN THE PIEDMONT REGION

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Abstract.—Reduced-impact forestry uses best management practices (BMPs) during operations to minimize soil erosion and sediment delivery to streams and to maintain or improve site productivity. However, the efficacy of specific types of BMP implementation is not widely documented. This review synthesizes recent research that investigated contemporary BMP implementation and effectiveness in water quality protection associated with the following forest management operations: forest roads and skid trails, streamside management zones, harvesting, site preparation, and stream crossings. The review concentrates on studies conducted in the Piedmont region of the eastern United States and facilitates integration and comparison with forestry BMP effectiveness research from the western United States. General results indicate that the most serious water quality issues are associated with bare soil conditions that are hydrologically connected to streams by roads, skid trails, or concentrated flows. Future research should determine sediment delivery ratios for forest road and skid trail approaches to stream crossings in order to develop and implement management strategies for minimizing sediment that has the highest probability of reaching the stream.

INTRODUCTION

Sediment is one of the most frequently cited water quality concerns associated with forestry operations (Grace 2002, Riekerk et al. 1989, Stuart and Edwards 2006) and is consistently ranked among the top 10 causes of river and stream impairment in the United States (U.S. Environmental Protection Agency 2003). Streams flowing through forested land generally have lower sediment concentrations relative to agricultural or urban areas, owing largely to the presence of the forest floor. The forest floor is composed of leaf litter and woody debris, which prevent soil erosion in a variety of ways. The forest floor covers bare soil and prevents sediment detachment from rainfall droplets. The forest litter layer, humus, and mineral soil have high infiltration capacities that are rarely exceeded, even by intense rain events. When surface runoff does occur, litter decreases the velocity of overland flow and acts to trap sediment.

Typical forest operations include access road construction and maintenance, installation of water control structures and stream crossings, harvesting and thinning, skidding, building log decks, fireline construction, burning, and site preparation. Each of these operations increases the percentage of bare soil within a watershed, thus increasing soil erosion and the potential for sediment delivery to streams. Forest cover removal generally results in short-lived streamflow increases as a result of decreased evapotranspiration (McGuire and Likens 2011). Increases in stormflow volumes and peakflows can accelerate within-channel erosion.

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Forest operations commonly occur within the drainage areas of zero-, first-, and second-order streams. These headwater streams may be ephemeral, intermittent, or perennial. Headwater streams compose more than two-thirds of the cumulative drainage length of river basins and link riparian and upland habitats to downstream ecosystems by providing streamflow, physical habitat, allochthonous organic material, and aquatic life (Benda et al. 2005, Freeman et al. 2007). Therefore, headwaters can govern downstream hydrologic conditions and water quality on a regional scale. For example, Dodds and Oakes (2008) stress the importance of riparian buffers in headwater reaches for the protection of downstream aquatic ecosystems.

Reduced-impact forestry uses best management practices (BMPs), which have proven to be generally effective in minimizing sediment inputs to streams (Aust and Blinn 2004, Wang and Goff 2008, Ward and Jackson 2004). However, BMP implementation does not eliminate sediment delivery to streams altogether. For example, in a review of three paired watershed studies in the eastern United States, Edwards and Williard (2010) calculated that BMP implementation reduced sediment by 53 to 94 percent. Often, BMP failures that contribute sediment to streams are non-uniformly distributed and occupy relatively small proportions of the total forest operational area. Rivenbark and Jackson (2004) estimated that approximately 0.33 to 0.4 percent of industrial forest land in the southeastern portion of the eastern United States' Piedmont physiographic province is contributing to streamside management zone (SMZ) failures at any given time.

Much work has yet to be done to understand both the spatial distribution of BMP failures within a watershed or operational area and the causes of BMP failures. For example, slope steepness, surface runoff contributing area, topographical feature type (e.g., gullies and swales), bare soil percentage, and their interactions have been used to aid in the characterization of sediment problem areas (Rivenbark and Jackson 2004).

Evaluation of reduced-impact forestry practices to minimize soil erosion and sediment delivery to streams is particularly relevant for the Piedmont. For more than a century before the 1930s, poor agricultural practices associated with row crop agriculture of corn, cotton, and tobacco caused extensive soil loss, gully formation, and aggradation of stream channels across the Piedmont, particularly in the southern states. Trimble (1985) describes an era of "land rotation," whereby exhausted farmland was abandoned and left to regrow, while forested land was cleared for new farms. This practice resulted in a highly eroded landscape, with sediment-laden stream channels and valley bottoms. Soil loss across the Piedmont has been estimated to be 60 cm or more (Trimble 1985). Although this region is now mostly forested, Piedmont streams continue to export these legacy sediments; this ongoing process confounds the quantification of contemporary land use effects on stream sedimentation (Jackson et al. 2005).

In addition, suspended sediment production from Piedmont forestry operations is high in comparison to mountainous and coastal plain sites of the southeastern United States because of the interaction between site preparation intensity and topographic relief (Riekerk et al. 1989) and clay-rich soils. Industrial forest operations are ubiquitous throughout the Piedmont. The anticipated increase in demand in the South for forest products (Anderson and Lockaby 2011) heightens the importance of understanding how well reduced-impact forestry practices perform in protecting stream water quality under various scenarios that may include increased stand entry, shorter rotations, and higher overall production over fewer forested areas.

Unlike well-known research sites in the Northeast, such as Coweeta (North Carolina), Hubbard Brook (New Hampshire), Fernow (West Virginia), and Leading Ridge (Pennsylvania) (Ice and Stednick 2004), the Piedmont physiographic province lacks a cohesive research unit. However, many recent studies have been conducted in this region regarding the effects of contemporary reduced-impact industrial forest operations on soil erosion and sediment delivery to streams. The objectives of this review are to consolidate and organize study findings by forest operation, including recent unpublished graduate theses; evaluate BMP performance for specific operations; and identify future research needs to minimize sediment delivery to streams.

FOREST OPERATIONS AND SEDIMENT IN THE PIEDMONT

Harvesting and Site Preparation

Timber Harvesting

Generally, harvesting itself does not substantially increase soil erosion. However, skid trails, log decks, and roads commonly cover 2 to 10 percent of logged sites (Kochenderfer 1977) and represent the most significant threat to water quality from forest operations due to an increase in erosion potential resulting from bare soil exposure, compaction, and increased surface runoff. Nutter and Douglass (1978) defined "soil-loss tolerance" for traditional agriculture (e.g., row crop agriculture) as the maximum average annual rate of soil erosion that permits a high level of productivity to be sustained economically and indefinitely. Soil-loss tolerance ranges from 4.4 to 11.2 Mg/ha for intensively managed (fertilized and site prepared), "good" agricultural soils in the Piedmont. The authors contended that most harvest methods would not exceed the soil-loss tolerance for agricultural soils and recommended that following harvest, there should be no site preparation that would expose additional mineral soil on slopes greater than 15 percent. This recommendation indicates an awareness of the potential for high rates of soil loss owing to the interaction between slope steepness and intensive site preparation practices that expose bare soil.

Pye and Vitousek (1985) estimated soil erosion rates resulting from clearcut harvest of 22-yr-old loblolly pine (*Pinus taeda*), followed by site preparation in the Piedmont of North Carolina. The study location was characterized by gentle slopes (0 to 10 percent) and clayey, kaolinitic, thermic Typic Hapludult soils. Three blocks (5 ha each) were clearcut, with half of each block either stem-only or whole-tree harvested. One half of each harvest treatment was drum chopped. The other half of each harvest treatment was sheared and windrowed, and the inter-windrow areas were disked. Most of the windrows were burned, but burning was unsuccessful for the drum-chopped areas. Finally, the four resultant treatment combinations were halved. Herbicide was applied to one half and not to the other. The split-split plot experimental design was replicated in each of the 3 blocks, which resulted in 24 plots. Soil erosion was measured with sediment traps for 1 year, beginning 9 months after site preparation. Although the drum-chopped plots produced minimal erosion, the windrowed sites produced a mean of 6.8 Mg/ha. This study shows that substantial soil erosion may occur even on gentle slopes when site preparation practices such as windrowing are implemented that remove or bury the forest floor. In addition, it also demonstrates that soil erosion may be effectively controlled by forest practices that minimize areas of bare soil.

In general, mechanized harvest operations compact soils, thus increasing bulk density and decreasing both aeration porosity and saturated hydraulic conductivity (Campbell et al. 1973). Gent et al. (1984) investigated changes in soil physical properties to a depth of 0.3 m for clayey, kaolinitic, thermic, Typic Hapludult soils in the Piedmont of North Carolina in response to whole-tree harvesting (low traffic area), skidding (high traffic area), and site preparation methods that included shearing/windrowing/double disking or chopping/burning. Soils were slightly above field capacity during harvest and site preparation. Soil physical properties of skid trail plots were impacted to a greater depth (0.22 m) in comparison with whole-tree harvest plots (0.17 m). Disking restored soil physical properties to preharvest levels in the upper 0.07 to 0.12 m of soil. This study is further evidence that the greatest impacts to soils during a typical harvest operation are associated with highly trafficked, bare soil areas such as roads and skid trails. In addition, on sites with steeper slopes, decreased saturated hydraulic conductivity can increase overland flow and therefore, soil erosion potential.

Grace and Carter (2001) quantified the effect of harvesting and site preparation on sediment and runoff yield from a 20-yr-old loblolly pine plantation with sandy loam soils and slopes ranging from 3 to 15 percent in the southern Piedmont in Alabama. Following a 25-ha clearcut, site preparation treatments were: (1) shearing, ripping, bedding, and machine planting on contour; and (2) machine planting on contour. Treatments were compared with an unharvested control site. During the 20-month study period, soil erosion rates were 0.08, 0.16, and 1.02 Mg/ha for the unharvested control, Treatment 1, and Treatment 2, respectively. The more intensively site-prepared plot (Treatment 1) was characterized by greater surface cover and roughness than Treatment 2 and thus greater protection against soil loss resulting from several high-intensity rain events. This finding indicates that rainfall timing and intensity may greatly influence soil erosion rates associated with forestry practices and reflects the apparent effectiveness of BMP implementation. In addition, the results of this study emphasize the importance of forestry operations (e.g., bedding) that maintain or create adequate surface roughness to allow for infiltration and decreased velocity of surface runoff. However, more studies are needed that quantify not only erosion rates from harvest operations, but also sediment delivery to adjacent water bodies in order to evaluate and improve low-impact forestry practices. For example, Hewlett (1979) estimated that for a typical forest operational unit, 5 percent of the detached soil reaches the stream channel.

Biomass Harvesting

In response to current woody biomass demand, chipping of logging residues, such as limbs, tops, and other nonmerchantable material is being incorporated into some conventional timber harvesting operations to produce biomass fuel chips. Despite many benefits of biomass as an alternative energy source, there is some concern that the use of nonmerchantable material for energy production at the expense of erosion control may increase soil loss and stream sediment concentrations. Barrett et al. (2009) used the universal soil loss equation as modified for forests (USLE - Forest) to estimate erosion rates on a biomass harvesting case study site in the Piedmont of Virginia (Dissmeyer and Foser 1984). Estimated annual erosion rates for the biomass harvest ranged from 7.2 to 19.3 Mg/ha as compared with erosion rates of less than 2.2 to 11.2 Mg/ha for a similar conventional Piedmont harvest. Some states have already begun making additional recommendations for BMP implementation for biomass harvests. The authors concluded that more research is needed regarding the effects of biomass versus conventional harvesting on soil erosion before additional BMPs for biomass harvesting are recommended.

Roads, Skid Trails, Stream Crossings, and Streamside Management Zones

Soil erosion increases associated with forest roads and trails have been widely identified as the dominant nonpoint source of sediment pollution attributable to forest silvicultural activities (Croke and Hairsine 2006; Grace 2002, 2005; Jordan 2006). Recently, the U.S. Court of Appeals of the Ninth Circuit ruled that logging roads should be considered point sources of pollution, therefore deciding that forest roads cannot be considered exempt from National Pollutant Discharge Elimination System (NPDES) permit requirements of the Clean Water Act under the Silvicultural Rule (Boston and Thompson 2009, U.S. Court of Appeals for the Ninth Circuit 2011). The Ninth Circuit ruled that forest roads are point sources when runoff is confined and re-routed through well-defined conduits, such as ditches and culverts, which ultimately flow and transport sediment into streams and rivers. Although the ruling currently applies to roads within the jurisdiction of the Ninth Circuit in Oregon, both public and privately owned forest roads throughout the Nation may require NPDES permits. This ruling emphasizes the importance of forest roads to water quality, forest operations, and national water policy decisions.

Roads

Forest roads are an integral component of forest harvesting operations, and timber harvests are conducted on approximately 4,000 km^2 of Virginia forest every 4 to 5 years. The potential for water quality degradation due to forest roads is widely recognized (Luce 2002). The degree of water quality impacts of forest road erosion depends on the delivery ratio of soil erosion to streams. Sediment is primarily delivered to streams through surface overland flow. Hydrologic connectivity between the road and stream networks depends on factors such as gully formation (Croke and Mockler 2001, Wemple et al. 1996) and mean annual precipitation (National Research Council 2008), but is inversely proportional to water control road features, such as waterbars, turnouts, and relief culverts (National Research Council 2008). Lakel et al. (2010) and Ward and Jackson (2004) found sediment delivery ratios from forest operations (including roads) to be approximately 10 to 25 percent, but forest roads alone can have higher delivery ratios. Dymond (2010) examined the influence of forest roads on water yield and concluded that road density effectively increased watershed stream density and stream flashiness. This conclusion implies that roads disproportionately increase water yields and sediment.

In a catchment modeling study of road effects on hydrology in two heavily logged, small catchments on the western slopes of the Cascade Mountains in the Pacific Northwest, Storck et al. (1998) used the Distributed Hydrology-Soil-Vegetation Model (DHSVM) and found that forest roads increased peak flows for the largest storm events by approximately 17 percent. However, Surfleet et al. (2010) found that roughly 25 to 50 percent of DHSVM-simulated storm volumes and peak flows for road ditches were outside the uncertainty bounds of a generalized likelihood estimation procedure. This result indicates substantial variability in modeled road runoff and emphasizes the need for studies that evaluate uncertainty in both model input parameters and predictions to evaluate model performance in accurately representing field hydrologic and soil erosion processes.

Road contribution of sediment to total export at the watershed and basin scale is highly variable. Turton et al. (2009) studied sediment yield to streams for unpaved roads in Oklahoma and estimated that roads may contribute up to 35 percent of the total sediment load for a large watershed (715 km^2). However, Sheridan and Noske (2007) found that near-stream unsealed forest road surfaces contributed only 4.4 percent of the total sediment load for a 135-km^2 watershed in southeastern Australia. Gravel application to bare road surfaces substantially decreases soil erosion (Kochenderfer and Helvey 1987).

Skid Trails

Wade et al. (2012) used a randomized complete block design to evaluate several skid trail closure techniques and ground cover BMPs for their performance in bare soil stabilization and erosion control. The study location was in the Virginia Piedmont, with slopes of 10 to 15 percent and sandy clay loam, fine, kaolinitic, mesic, Typic Kanhapludults. Treatments were: (1) water bars (control); (2) water bars plus seeding; (3) water bars, seeding, and straw mulch; (4) water bars plus hardwood slash; and (5) water bars plus pine slash. Sediment was captured at the base of the plots by geotextile sediment filtration bags and weighed following rain events and at monthly intervals to obtain sediment weights.

Three soil erosion models were used to compare measured soil erosion with modeled soil erosion: USLE, the Water Erosion Prediction Project (WEPP) for forest roads, and the revised universal soil loss equation v.2 (RUSLE2). Mean annual erosion rates for the treatments were 137.7 Mg/ha for the control, 31.5 Mg/ha for the seeding treatment, 8.9 Mg/ha for the hardwood slash treatment, 5.9 Mg/ha for the pine slash treatment, and 3.0 Mg/ha for the mulching treatment. In general, USLE, WEPP, and RUSLE2 correctly predicted the order in which treatments afforded the best erosion control, which demonstrates their utility in BMP evaluation. Results indicate that for areas of high erosion potential, water bars alone may be a poor choice for water quality protection due to their lack of soil stabilization. The best choices appear to be application of logging slash (see also Sawyers et al. 2012) or mulching. Slash may be the most advantageous choice because it is readily available on harvest sites and has a slower decomposition rate than straw mulch.

Stream Crossings

Sediment delivery is of particular importance at forest road stream crossings (Lane and Sheridan 2002), which represent the most direct pathway for overland flow and sediment to stream channels. Therefore, sediment delivery ratios for forest road approaches to stream crossings should be determined in order to implement management strategies for minimizing sediment that has the highest probability of reaching the stream. The 2010 Virginia Department of Forestry (VDOF) BMP audit indicated that improper BMP implementation at stream crossings was the most important problem identified from forest operations in Virginia (Lakel, pers. comm.).

Forest road approaches to streams, as well as stream crossings, have the potential to deliver the greatest quantity of sediment to streams during forest operations (Carroll 2008, Swift 1986, Taylor et al. 1999). Installation of crossing structures requires heavy equipment trafficking over sensitive stream banks, through riparian zones, and potentially in the stream channel itself. In addition to sedimentation from equipment, sediment can run directly to streams from forest road approaches. Fords introduce sediment to streams as vehicles drive over the stream bed. Culvert installation, which involves excavation and fill work, can introduce 10 or more times the amount of sediment than a logging operation (Swift 1986, Taylor et al. 1995).

Taylor et al. (1995) make a strong case for the use of portable longitudinal glued-laminated (glulam) deck timber bridges for stream crossings on temporary low-volume roads. Advantages of portable timber bridges include their light weight and ease of fabrication, transport, installation, and removal. Because portable timber bridges are re-usable (up to 10 times or more), installation cost is comparable to that of a permanent corrugated metal culvert at $2,550 per installation (Taylor 1995). In addition, a major advantage for water quality protection is that glulam bridges may be installed and removed with skidders or hydraulic knuckleboom loaders without operating the equipment in the stream channel (Carroll 2008).

McKee et al. (2010) surveyed logging contractors from the major physiographic regions of Virginia (Mountains, Piedmont, and Coastal Plain) to better understand the most typical stream crossing types installed, the total cost associated with purchasing and installing stream crossings, and type and cost of closure BMP implementation. The authors found that more stream crossings are used for skidders than for log trucks across all physiographic regions. Bridges are most commonly used for stream crossings in the Piedmont, whereas culverts predominate in the mountains. Associated costs are highest for steel bridges, followed in descending order by costs for wooden bridges, culverts, and fords. The most commonly used stream crossing closure BMPs include a combination of waterbars, seeding, and mulch. Additional BMPs are covering roads with slash and installing water turnouts. These BMPs have been shown to be generally effective in water quality protection (Carroll 2008). The cost of BMP closure implementation ranged from $445 to $655 per crossing, with greater costs associated with BMP installation in the Mountain region.

Carroll (2008) evaluated upstream and downstream water quality, including sediment concentration, for 23 operational stream crossings in the Virginia Piedmont. Stream crossing structures included portable bridges, culverts backfilled with poles, culverts backfilled with earth, and reinforced fords. Water quality was monitored during four operational phases: preinstallation, postinstallation, during harvest, and post-road closure. Overall, this study found that portable bridges are the most effective for water quality protection, but that performance is also governed by road standards and approach characteristics. Importantly, this study found that the increased SMZ removal associated with permanent stream crossings may result in greater stream temperature increases.

Streamside Management Zones

In a watershed-scale experiment, Lakel et al. (2010) evaluated the sediment trapping efficacy of various SMZ widths under different levels of thinning following forest harvesting and site preparation in the Piedmont of Virginia. The study examined SMZ widths of 7.6 m, 15.2 m, and 30.4 m in which no thinning occurred, as well as 15.2-m, thinned SMZs. All SMZ widths performed equally well in trapping sediment, which indicates that SMZ effectiveness is controlled by factors other than width. Keys to SMZ effectiveness in trapping sediment include the presence of an intact forest floor and slope steepness, suggesting that SMZ width prescriptions should be made on a site-by-site basis. The implication is that through better understanding of the processes that control soil erosion, as well as BMP effectiveness in minimizing erosion and sediment redistribution, both water quality and site productivity objectives may be optimally achieved.

Lakel et al. (2010) also provided important data on soil erosion to sediment delivery ratios, determining that 3 to 14 percent of sediment from the harvested area reached the SMZ. This study not only examined SMZ sediment trapping effectiveness, but also quantified the amount and percentage of soil erosion and sediment delivery from harvest site preparation, roads, skid trails, decks, and firelines. As is most commonly found, highly compacted and bare soil areas such as roads, skid trails, and firelines contributed the most sediment to the SMZ. These areas of high erosion potential often represent a small percentage of the total operational area, but contribute the most sediment per unit area.

Rivenbark and Jackson (2004) examined the spatial frequency and physical characteristics of ephemeral concentrated flow paths entering SMZs for 30 clearcut and site-prepared industrial forest operational units in the Georgia Piedmont. The impetus for this study was to aid in the understanding of where and why BMPs fail to prevent sediment from being transported to stream channels. Breakthroughs were defined as surface overland flow (and sediment) pathways that invaded the SMZ and reached the stream channel. Areas of convergence (swales) and gullies accounted for about 50 percent of all breakthroughs. Concentrated runoff from roads and skid trails was identified as the cause of 25 percent of the breakthroughs. In general, large contributing areas (mean = 0.4 ha), minimal litter cover, and steep slopes characterized the locations where breakthroughs occurred. In some cases, overland flow traveled more than 30 m through SMZs before reaching the stream channel. The authors concluded that improvements to increase BMP effectiveness include maximizing ground cover, improving road runoff dispersal, increasing resistance to probable surface overland flow paths, and selectively increasing SMZ widths in problem areas.

Swift (1986) examined sediment transport distances below forest roads during and 9 months after construction in the Appalachian Mountains of western North Carolina. The objectives of this study were to evaluate the effectiveness of filter strip standards in the southern Appalachians and to test the efficacy of mulch or grass on fill slopes and of obstructions to flow within filter strips. Guidelines for filter strip widths in the eastern United States originated from the Trimble and Sartz (1957) experiment, where the slope distance of sediment transport was determined from 36 open-top culverts on partially graveled roads at the Hubbard Brook Experimental Forest in the White Mountains. Slope steepness below the road was used to make recommendations for filter strip widths to effectively trap sediment (Trimble and Sartz 1957).

Swift (1986) found that grassed fill slopes, filter strips with intact forest litter cover, and brush barriers, such as logging slash and hay bales, were most effective in reducing sediment deposit length. Importantly, this study showed that filter strip width may be reduced if the aforementioned BMPs are implemented correctly, again implying that increased filter strip width does not necessarily mean that more sediment will be trapped. Filter strip width recommendations should be made on a case-by-case basis and should take into account slope steepness, forest litter layer condition, erosion potential from human-made drainage structures (e.g., road ditches and culverts), natural areas of convergence (e.g., gullies and swales), soil erosivity, and climate. In addition, the duration of soil exposure should be as short as possible and limited to periods of minimum rainfall intensity.

Research Needs

Anderson and Lockaby (2011) identified the following four categories of research gaps related to forest operations and stream sedimentation: timber harvesting effects on water yield and water quality, temporal and spatial scale of sediment delivery, sediment and water yield from roads, and assessing the effectiveness of BMPs. Increases in stormflow volumes and peakflows following harvest operations may increase within-channel erosion, particularly in streams that are heavily impacted by legacy sediments. Legacy sediments confound evaluations of contemporary forest management practices because it is difficult to separate water quality impacts from past and present land use (Jackson et al. 2005). Incorporation of tracers (isotopic and radionuclide) to track sediment movement and statistical tools (Aikaike's Information Criterion and multivariate approaches) in current and future forestry studies could greatly improve understanding of different sediment sources (Anderson and Lockaby 2011).

We know that the majority of sediment associated with forest operations is generated from relatively small problem areas that are often non-uniformly distributed throughout the operational area. Often, these problem areas are associated with stream crossings and their associated skid trail and haul road approaches. Better quantification of soil erosion to sediment delivery ratios under various levels of BMP implementation is critical to improve the efficacy of reduced-impact forest practices. We also know that when BMPs are properly installed during forest operations, water quality generally remains unimpacted (Aust and Blinn 2004). However, more cost-benefit analyses of BMP implementation are required to achieve the major objectives of sustainable productivity and water quality protection at minimal cost.

In addition, more research is necessary to understand the impact of major rainfall events on the performance of BMPs in reducing soil erosion and sediment redistribution. Many studies are short in duration (<4 years) and may be heavily influenced by one or more major storm events. Conversely, a lack of rainfall may give undue credit to BMP effectiveness in protecting water quality. Simply put, rain events govern study findings (Anderson and Lockaby 2011). Rainfall simulation studies allow researchers to test BMP effectiveness over any desired range of rainfall conditions.

Much of the research specifically regarding forest roads and water quality in the United States has originated in the West (Anderson and Potts 1987, Litschert and MacDonald 2009, Reid and Dunne 1984). Far fewer studies investigate sediment delivery from forest roads in the East, with the exception of research at Coweeta and Fernow. Intensive forest management in the Piedmont has given rise to an extensive network of forest roads and stream crossings in this region, where sediment delivery to upland headwaters has important water quality implications for the protection of downstream water bodies (Freeman et al. 2007). It is impractical, if not impossible, to monitor stormflow and soil erosion from all road and skid trail crossings through field experimentation. Therefore, models that are readily applicable to land management programs and that accurately represent hydrologic and soil erosion processes at the catchment scale are critical to predict site- and regional-scale impacts to water quality. These hydrologic and soil erosion models may be used to assist land managers in identifying high-risk areas for erosion and implementing appropriate BMPs for water quality protection. However, models must be evaluated to determine their utility in accurately representing field hydrologic conditions and sediment delivery ratios across a broad range of conditions.

Several state and federal agencies, such as VDOF and the U.S. Department of Agriculture (USDA), Forest Service are interested in determining the applicability of the WEPP model for predicting sediment production from forest roads. The WEPP model is a physically based soil erosion and hydrologic model developed by the USDA Natural Resources Conservation Service and Forest Service that estimates soil loss and sediment yields from hillslope erosion at the small catchment scale (Flanagan and Nearing 1995). This model is capable of partitioning soil loss and sediment yields associated with roads into individual road features, such as the road surface, cutslope, fillslope, ditch, and lower hillslope (Fu et al. 2010). Previous studies have shown that WEPP is a useful tool for estimating soil erosion from surfaces with low infiltration rates, such as forest roads, where overland flow is the dominant hydrologic process (Croke and Nethery 2006, Dun et al. 2009, Elliot et al. 1999, Fu et al. 2010, Grace 2005, Laflen et al. 2004), but it has not been evaluated in the field for a wide range of forest roads and rainfall conditions.

Measurement of sediment yield and sediment delivery is highly variable, even under well-controlled field experiments. For example, Fu et al. (2010) describe variation as a result of differences in methodology. Much uncertainty exists in measured sediment yields when sediment trap data are used to estimate total sediment yields. Roadside sediment traps effectively sample coarse sediment yields but may miss the finer sediment fractions of total sediment yield. In addition, road erosion rates display a wide range of variability across different areas owing to differences in rainfall timing, frequency, and intensity, as well as topography, slope, frequency of traffic and maintenance, and surface type. For example, Brooks et al. (2006) state that because measurements of soil erosion are so highly variable, predicted erosion rates should not be assumed to be more accurate than ± 50 percent. Laflen et al. (2004) reviewed published studies related to WEPP goodness-of-fit and suggest that without calibration, WEPP performs as well as USLE - Forest. When controlled field experiments or databases of site-specific characteristics are used to parameterize the model, WEPP has the potential to be an effective tool for watershed managers.

Because WEPP mainly considers overland flow, it is currently best suited to predict runoff and soil erosion on surfaces where overland flow dominates hydrologic processes. Substantial variability exists in model predictions of runoff and sediment yield in disturbed forest settings that are dominated by subsurface flow processes (Wu et al. 2000). However, a strong case can be made that for modeling sediment yield and delivery, which are governed by overland flow, WEPP performs best where it is needed the most (i.e., forest roads and skid trails). Therefore, WEPP can be very useful for small, high-risk road segments, such as road approaches to stream crossings. However, to compare relative sediment delivery ratios between roads and other forest practices not dominated by overland flow, model performance must be improved.

Further modifications to the processes that control subsurface flow within the WEPP model are necessary to better estimate runoff and erosion at the catchment scale. In addition, subsurface flow interception by forest roads should be considered in future modifications to the model. Controlled field experiments on forest roads and other disturbed forest areas (harvested, burned, site prepared) across a broad range of landscapes are necessary to test WEPP representation of hydrologic and soil erosion processes and evaluate uncertainty in model predictions.

SUMMARY

This review concentrated on soil erosion and sediment delivery associated with reduced-impact forest operations in the Piedmont region. General results indicate that soil erosion per unit area is greatest for roads and skid trails, while comparatively less for harvested and site-prepared areas. Implementation of BMPs is most effective in water quality protection when prescriptions are made on a case-by-case basis and guided by characteristics such as percentage of bare soil, slope steepness, topographical features such as gullies and swales, and rainfall timing and magnitude. Much more is known about soil erosion rates, as opposed to sediment delivery ratios for various forest practices.

Future research should use sediment tracing methods to identify sediment source areas that are often a small percentage of total forest operations and non-uniformly distributed. Coupling of well-controlled hydrologic/soil erosion field studies and soil erosion modeling is beneficial because it provides much-needed measurements of soil erosion and sediment delivery with which to calibrate and evaluate soil erosion model performance, as well as BMP performance under changing land use scenarios.

ACKNOWLEDGMENTS

The authors thank VDOF and the Virginia Water Resources Research Center at Virginia Tech for their funding support for this paper.

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