Sediment Trapping by Streamside Management Zones of Various Widths after Forest Harvest and Site Preparation

William A. Lakel III, Wallace M. Aust, M. Chad Bolding, C. Andrew Dolloff, Patrick Keyser, Robert Feldt

Abstract: Recommended widths for streamside management zones (SMZs) for sediment protection vary. The objectives of this study were to compare the effects of SMZ widths and thinning levels on sediment moving through SMZs. 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 (*Pinus taeda* L.). Treatments were 30.4-, 15.2-, and 7.6-m-wide SMZs without thinning and 15.2-m-wide SMZs with thinning. Three to seven treatments replicated within four blocks created a randomized incomplete block design. Erosion rates from watersheds and sediment trapping within SMZ treatments were monitored with modeling and sediment pins. A second study evaluated 24 subwatersheds within eight watersheds. Three subwatersheds were located within each watershed so sediment traps collected inputs into SMZs from harvest site-prepared areas, firelines, or at streams. SMZ treatments had no significant differences regarding sediment trapping. All SMZs widths were generally effective in trapping sediment. Within the 16 intermittent-perennial watersheds and 24 ephemeral subwatersheds, erosion to sediment delivery ratios from harvests ranged from 3 to 14%. For ephemeral stream subwatersheds, 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. In three subwatersheds, sediment penetrated SMZs due to channelized flow from failed or inadequate water controls on roads and firelines. Results support the common recommendation for SMZ widths of 15.2 m in which partial harvests may occur and emphasize the importance of implementation of best management practices for roads and firelines. FOR. SCI. 56(6):541–551.

Keywords: streamside management zones, riparian forests, forest operations, sediment, best management practices

STATE FORESTRY AGENCIES have adopted the use of streamside management zones (SMZs) as part of their standard forestry best management practices (BMP) guidelines (Blinn and Kilgore 2001) because research indicates that SMZs potentially have several positive effects on environmental quality (Lynch and Corbett 1990, Castelle et al. 1994, Aust and Blinn 2004, McBroom et al. 2008). Vegetation and soil litter layers in SMZs slow surface water velocities, thereby trapping sediment and sediment-attached chemicals and nutrients (Beasley et al. 1986, Cooper et al. 1987, Beasley and Granillo 1988, Phillips 1989, Lowrance 1992, Castelle et al. 1994, Daniels and Gilliam 1996, Sheridan et al. 1999). SMZs shade the stream and protect against temperature increases (Swift and Messer 1971, Hewlett and Fortson 1982). Vegetation in SMZs take up nutrients and transform them into organic forms that are less harmful to water quality (Lowrance et al. 1984). Wetting and drying cycles of riparian areas favor transformations of inorganic nitrogen compounds into benign gaseous compounds through a series of aerobic and anaerobic soil processes (ammonification, nitrification, and denitrification) (Lowrance 1992, Daniels and Gilliam 1996, Lowrance and Sheridan 2005, Young and Briggs 2007). The litter and vegetation also stabilize stream banks and minimize stream bank erosion (Allmendinger et al. 2005). Although SMZs are recommended as BMP for a variety of water quality benefits, forestry BMP focus on the sediment-trapping benefits because sediment is generally considered to be the most important type of water pollutant associated with forest operations in the United States (Neary et al. 1989, Binkley and Brown 1993, Jackson et al. 2005).

SMZs are important for protection of water quality and they provide or enhance aquatic and terrestrial habitat for associated wildlife. SMZs may provide mature and more diverse forests and associated habitat in intensively managed forest landscapes (Murray and Stauffer 1995). Furthermore, SMZs provide both large and fine woody debris to the streams, thereby creating in-stream habitat and support for the food chain (Jones et al. 1999, Dolloff and Webster 2000). Erosion and associated sedimentation from forest operations can harm fish and other organisms directly and prevent successful reproduction by covering spawning habitat with silt. Fish species requiring clear water will perish or migrate, and fish species more tolerant of turbid water and muddy channels will dominate (Duda 1985). Fine sediment particles often damage gills of fish and organisms that fish feed on (Duda 1985, US Environmental Protection Agency 2000). Sediment increases turbidity, which can reduce

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photosynthesis by aquatic plants, further degrading habitat. The fine sediments often transport adsorbed pollutants such as pesticides, plant nutrients, and trace metals (Oschwald 1972). Long-term sedimentation can drastically alter stream characteristics and entire ecosystems permanently (Duda 1985, US Environmental Protection Agency 2000).

In addition to their water quality and habitat functions, SMZs are often productive timber sites. Thus, many landowners may be interested in minimizing potential monetary loss caused by leaving standing timber in SMZs while still providing society with desired water quality standards (Aust et al. 1996, Shaffer et al. 1998). BMP guidelines generally suggest that landowners can reduce costs of implementing SMZs by conducting partial harvests (Blinn and Kilgore 2001, Aust and Blinn 2004). However, little research has been done to specifically compare the efficacy of different widths of SMZs and partial harvests within SMZs from a water quality perspective. Forestry BMP guidelines vary considerably regarding riparian management and SMZ specifications (Blinn and Kilgore 2001, Aust and Blinn 2004). Furthermore, research on forestry riparian areas has seldom examined smaller headwater streams but has commonly focused on larger streams. However, recognition of the potential sediment contributions of headwater streams has increased (Jackson et al. 2001, MacDonald and Coe 2007).

In the eastern United States, state forestry agency recommendations for SMZ widths vary from 7.6 to ≥ 39.6 m for standard forest operations. Blinn and Kilgore (2001) summarized perennial stream SMZ recommendations for 33 eastern states (north and south) and found that 25 eastern states recommended SMZs of ≤15.2 m and 6 recommend SMZs ≥15.2 m. Four states recommended SMZs as narrow as 7.6 m and 1 state recommended SMZs >30.2 m. One state did not make specific width recommendations, and one state suggested that widths would be site-specific. Fewer eastern states (26) had specific recommendations for intermittent streams, but 80 and 30% recommended SMZ widths ≤15.2 and 7.6 m, respectively. The review of Blinn and Kilgore (2001) also indicated that specifications regarding partial harvests within SMZs are provided by 70% of the eastern states.

Trimble and Sartz (1957) conducted one of the first evaluations of different SMZ widths required to prevent forest road sediment from entering streams. They evaluated 36 lightly graveled road sections drained by open-topped culverts on a newly reconstructed forest road in the Hubbard Brook Experimental Forest within the New Hampshire White Mountains. The roads were steeper than current BMP recommend with slopes as great as 20%, although the average slopes were 10%. Trimble and Sartz (1957) developed three generalities for SMZs that are still widely applied by state forestry BMP recommendations. First, they recommended a minimum SMZ width of 7.6 m (25 ft). Second, they advocated increasing the SMZ width by 0.6 m (2 ft) for every 1% increase in sideslope. Finally, they recommended a minimum of 15.2 m (50 ft) SMZ for sensitive areas such as municipal watersheds. Their recommendations were based on slope distance; yet many subsequent recommendations are based on horizontal distance.

Swift (1986) evaluated two forest roads in the Coweeta Experimental Forest in the Blue Ridge Mountains of North Carolina. The roads had grades less than 10% and adequate water control structures and were graveled or grassed soon after construction. Based on evaluations of 88 sediment plumes from the roads, Swift (1986) recommended that the minimum SMZ width should be 9.7 m (32 ft) with an additional 0.12 m (0.40 ft) for every additional 1% slope, if brush filters were in place between the sediment and stream. If brush filters were absent, Swift (1986) recommended a 13.1 m (43 ft) buffer with an additional 0.42 m (1.39 ft) per 1% slope. Megahan and Ketcheson (1996) conducted a similar study on 280 sediment deposits from forest roads in Idaho. They concluded that the travel distance of the road sediments was a function of sediment volumes, quantity of downed woody material, and basal area of standing vegetation, rockiness, and litter depth. They modeled sediment travel and suggested that modeling could be used to estimate the length of sediment travel. They suggested a variable-width SMZ based on modeled sediment travel distance and suggested that SMZs merely needed to be wider than the estimated travel distance.

Keim and Schoenholtz (1999) evaluated the impact of disturbance within SMZs in the Loess Hills region of Mississippi. A nonharvested control and three 30-m-wide SMZ disturbance treatments were evaluated. The three SMZ disturbance treatments were unrestricted harvest, skidder cable removal without traffic, and no harvest SMZs. They found that streams in logged watersheds had three times greater sediment concentration. Although their skidder cable logged and no harvest SMZs were more similar to the nonharvested control, the SMZs did not trap sediment from outside of the SMZ. They speculated that this was due to a combination of existing gullies and creation of new gullies in the erosion-susceptible loess deposits. They believed these gullies allowed the sediment to evade the SMZ.

Bren (1998) proposed the use of variable-width SMZs rather than fixed widths. Bren evaluated a large watershed in Australia by modeling the SMZ effects on water quality for subwatersheds ranging from perennial to ephemeral. Bren concluded that large perennial streams are less influenced by SMZs than are smaller perennial streams because larger streams have more complex loading. The modeling also indicated that convergent ephemeral head drains might be underprotected by fixed-width buffers, whereas divergent ephemeral drains along slopes may be overprotected by fixed-width SMZs.

Rivenbark and Jackson (2004) evaluated 30 sites in the Georgia Piedmont that had been clearcut and site prepared and evaluated the potential for sediment bypassing the SMZ. They found 187 breakthroughs and concluded that approximately one-half of the problems were associated with convergence areas and reactivation of gullies and 25% of the problems were specifically due to forest roads. Further evaluation of the sediment plumes in the breakthrough areas indicated that 86% of the breakthroughs would not penetrate a 30.4-m SMZ.

Ward and Jackson (2004) measured sediment accumulations at SMZ boundaries and contrasted these rates with modeled erosion estimates. Their data indicated that approximately 25% of the erosion from clearcut and site-prepared sites in the Georgia Piedmont is delivered to the SMZ.

White et al. (2007) simulated harvest runoff through forested filter strips under a range of forest floor removals in the Georgia Piedmont and found that sediment retention occurred even when the forest floor was totally removed. Based on their evaluations they concluded that a narrow SMZ would be sufficient for trapping coarse sediment, whereas a 16-m SMZ would trap the majority of sediment.

The literature indicates that sediment is a primary pollutant from forest operations and that SMZs can be important BMP for trapping sediment before it enters the stream. However, there are few designed watershed scale experiments that examine the influence of SMZ width and thinning levels on sediment trapping. Therefore, the major goal of this study was to evaluate the current Virginia SMZ recommendation (15.2-m SMZ with or without thinning) (Virginia Department of Forestry 2002) compared with wider (30.4-m SMZ) and narrower (7.6-m SMZ) SMZs to determine the effects of SMZ width and thinning on sediment trapping in headwater streams after forest harvesting and site preparation. A secondary goal was to evaluate the sediment inputs from harvesting-site preparation activities and fireline construction to the streams. Goals were accomplished by testing the following null hypotheses:

HO$_1$: Different SMZ widths and harvest levels (thinning) have no significant effects on harvest and site preparation-related sediments trapped within the SMZs.

HO$_2$: Sediment movement from harvesting site-prepared areas and firelines is not significantly affected by SMZs.

Methods

Study Sites

Sixteen first-order headwater streams and watersheds in the Piedmont physiographic region (Buckingham County, Virginia, 37°32′57″N latitude, 78°43′28″W longitude) were evaluated. Watersheds are in the upper James River basin that drains into the Chesapeake Bay. Elevations of the sites range from 150 to 360 m above mean sea level. January maximum and minimum temperatures average 8.3 and −2.8°C, and July maximum and minimum temperatures average 30.3 and 18.0°C (US Department of Agriculture Natural Resource Conservation Service 2004). Average annual rainfall for the sites is 1,070 mm. During the study, on-site rain gauges indicated that average annual rainfall on the sites was slightly below average at 1,020 mm. Sites had been subjected to nonsustainable agricultural practices and associated erosion from the mid-1700s to the late 1800s. The abandoned old fields naturally reverted to early succession pine forests followed by later succession hardwood forests (Gemborys 1974, Van Lear et al. 2004). The naturally regenerated, postagricultural forests were subsequently harvested once or twice during the 1900s. Sites were converted to loblolly pine (*Pinus taeda* L.) plantations during the 1950s–1960s, and plantations were subsequently harvested and planted two additional times.

Streams were intermittent with defined channels at the upper end of the watershed and became small perennial streams near the outlet (Table 1). Watershed sizes ranged from 5.9 to 72.1 ha with an average size of 29.7 ha. Monitored stream lengths averaged 540 m and ranged from 252 to 1,044 m. Sideslopes within the watersheds averaged

Table 1. Watershed, operational, and stream characteristics for the 16 watersheds used to evaluate the effect of streamside management zone (SMZ) width on sediment trapping by treatments

SMZ treatment	Stream no.	Watershed Area	Harvest area	Bare area (roads, decks, skid trails, and firelines) (m)	Stream channel width	Stream channel slope
		................(ha)	....		...........................(%)	....
7.6m SMZ	1	10.4	9.0	0.5	4.9	17.0
	2	72.1	69.3	1.8	4.8	17.6
	3	53.3	50.7	1.7	5.1	10.0
Average		45.2	43.0	1.4	4.9	14.9
15.2m SMZ THIN	1	9.2	7.5	0.8	4.9	12.5
	2	12.8	10.9	1.2	5.1	9.6
	3	54.4	45.6	1.8	4.8	4.8
Average		25.5	21.3	1.3	4.9	9.0
15.2m SMZ	1	7.8	6.7	0.4	3.3	5.5
	2	8.2	6.2	0.7	3.8	12.5
	3	14.5	12.8	0.7	5.7	3.3
	4	48.7	42.6	2.5	4.1	2.3
	5	70.2	66.1	1.9	3.5	5.0
	6	22.9	19.3	1.7	4.0	2.3
	7	26.0	23.4	1.5	3.1	11.9
Average		28.3	25.3	1.3	3.9	6.1
30.4m SMZ	1	16.3	11.4	0.6	3.4	4.9
	2	5.9	4.7	0.3	5.2	5.0
	3	42.8	39.5	1.5	4.9	5.0
Average		21.6	18.5	0.8	4.5	5.0
Overall average		29.7	26.6	1.2	4.4	8.1

25% and ranged from 10 to 65%. Soil textures are generally loams, silt loams, or clay loams with significant coarse fragments (US Department of Agriculture Natural Resources Conservation Service 2004). Upland soil series include Spears Mountain silt loam (fine, mixed, semiactive, mesic, typic hapludults), Fairystone channery loam (clayey-skeletal, parasesquic, mesic, typic hapludults), and Bugley channery silt loam (loamy-skeletal, mixed, semiactive, mesic, lithic dystrudepts), which are residuum formed from schists and phyllite. Riparian soils include Hatboro loam (fine-loamy, mixed, active, nonacid, mesic, fluvaquentic endoaquepts) and Delanco gravelly loam (fine-skeletal, mixed, semiactive, mesic, aquic hapludults) formed on schist and gneiss (Easterbrook-Walker et al. 2003, US Department of Agriculture Natural Resources Conservation Service 2004).

Treatments and Experimental Design

In 2001, Virginia Tech researchers and MeadWestvaco land management foresters examined more than 50 stands having potentially suitable streams and watersheds. Sixteen watersheds were selected according to the following criteria. Selected sites were of merchantable age and volume, were large enough to be operational harvests, and had suitable road access to facilitate harvesting, instrumentation, and monitoring. The selected watersheds were sufficiently large to ensure defined stream channels and water flow, while being small enough to facilitate monthly water quality sampling. Selected stands were loblolly pine plantations that would be clearcut and site prepared. Geology and soils were representative of the Piedmont region and relatively uniform within a block (US Department of Agriculture Natural Resources Conservation Service 2004). Locations and site conditions are provided in Table 1 and Figure 1.

After selection, watersheds were assigned to one of four blocks primarily based on a combination of proximity, watershed size, and site conditions (vegetation and soil). Next, four SMZ treatments were randomly assigned to the four watersheds within each of the four blocks. The four SMZ treatments were (1) 7.6-m width SMZ with no thinning (7.6m SMZ), (2) 15.2-m width SMZ with no thinning (15.2m SMZ), (3) 15.2-m width with 30–50% basal area removal by thinning (15.2m SMZ THIN), and (4) 30.4-m width SMZ with no thinning (30.4m SMZ). These four treatments generally capture the range of normal state agency recommendations for SMZs (Blinn and Kilgore 2001) and allow examination of thinning effects. Sediment pins were placed in the SMZs along three transects (upper, middle, and lower watershed) and monitored for 1 year before installation of operational treatments (Figure 2). Analyses of the pretreatment sediment data revealed no significant quantities of sediment between the watersheds before treatment installation, other than streambank erosion immediately adjacent to channels as reported by Easterbrook-Walker et al. (2003). After 1 year of preharvest measurements, the harvests and four SMZ treatments were installed during 2003–2004 as part of operational timber harvests. The 16 watersheds were clearcut harvested, site prepared with prescribed burning, and hand planted with loblolly pine. Within the 16 watersheds, the four SMZ

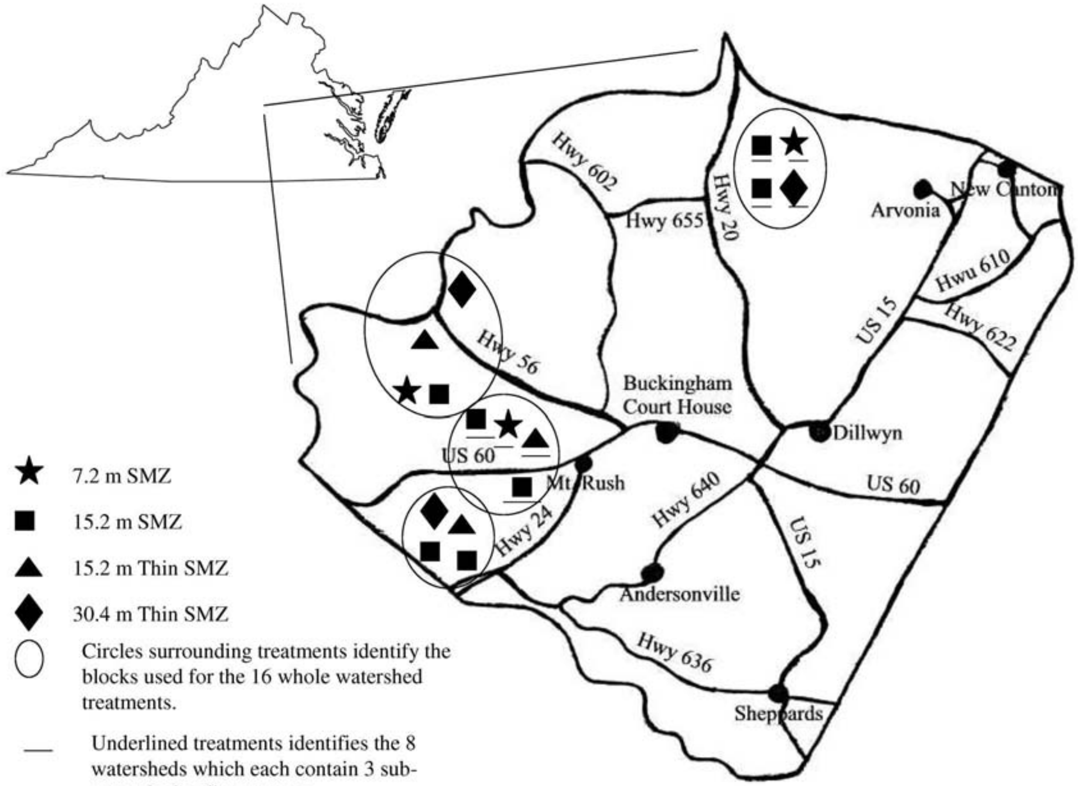

Figure 1. General vicinity map of the 16 SMZ treatment watersheds in Buckingham County, Virginia.

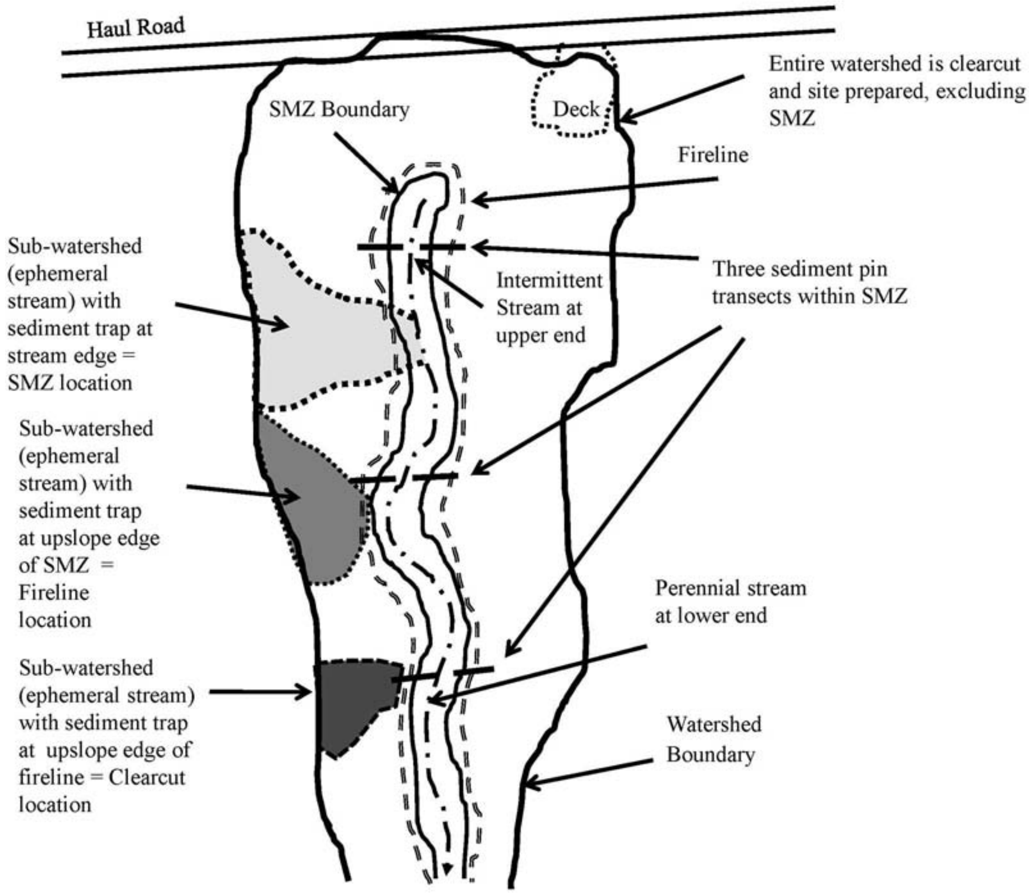

Figure 2. Conceptual representation of an idealized watershed (one of 16 watershed treatments) and operational categories. The USLE-Forest Version was used to estimate erosion within each operation category (harvest site-prepared areas, haul road, deck, SMZ, and firelines). Sediment pins were installed along three transects in the SMZ to quantify sediment deposition within the SMZ. Sediment traps were placed in 3 subwatersheds (SMZ, fireline, and clearcut locations) within 8 of the watersheds (24 subwatersheds) to quantify erosion from the forest operations, fireline and forest operations, and sediment deposition within the SMZ.

treatments (7.6m SMZ, 15.2m SMZ THIN, 15.2m SMZ, and 30.4m SMZ) were established on each side of the stream channel. The original study was designed as a randomized complete block design with all treatments occurring once in each block, but logger misinterpretation of delineated SMZ borders altered the number of replications. The four treatments were installed within at least three of four blocks, and final replications for the 7.6m SMZ, 15.2m SMZ THIN, 15.2m SMZ, and 30.4m SMZ treatments were three, three, seven, and three, respectively (Figure 1). Thus, data for this portion of the study were analyzed as an incomplete block design.

Field Measurements

Two major types of erosion and sediment data were collected within the 16 watersheds: modeled erosion estimates and sediment pins used to quantify sediment deposition. Immediately after harvest and site preparation, areas of SMZs, permanent haul roads, skid trails, and firelines were delineated within each watershed with a global positioning systems unit (Etrex Legend; Garmin, Olathe, KS). Harvest and site preparation boundaries and deck areas were digitized using aerial photographs for area calculations (Terrain Navigator Pro; Maptech, Amesbury, MA). The Universal Soil Loss Equation, as modified for forestland (USLE-Forest Version) (Dissmeyer and Foster 1984) was used to estimate the soil erosion potential from each disturbance type. The USLE-Forest Version was selected because it has been shown to generally produce reliable results from forestlands (Hood et al. 2002, Ward and Jackson 2004, Fu et al. 2010) and because it is sufficiently flexible for application to a variety of conditions (Croke and Nethery 2006). Five to seven USLE-Forest Version erosion estimation points were installed within each operational area for each of the 16 watersheds.

Beginning in June 2004, soil erosion in the SMZs was monitored using the erosion pins (Brooks et al. 2003) that had been installed preharvest along three equally spaced transects (upper, middle, and lower SMZ) (Figure 1). Along each transect and on both sides of the stream, erosion pins were installed and measured at 2.3, 4.6, 7.6, 15.2, 30.4, and 38.1 m from the center of the stream for a total of 36 erosion pins per watershed (Easterbrook-Walker et al. 2003). Erosion pin elevations were surveyed to known benchmarks as suggested by Brooks et al. (2003) with a transit and Philadelphia rod. Erosion pins were 0.6-m lengths of rebar inserted 0.3 m into the ground. The aboveground portions of the rods were measured to the nearest millimeter from the mineral soil surface. Rods were measured 2 years after harvest to determine erosion or deposition depth. Data were split by transect and analyzed via analysis of variance procedures for split-plot designs.

A subwatershed study was conducted to examine the sediment contributions of harvest operations (clearcutting, site preparation, roads, and skid trails) and firelines to the streamside management zones and streams. Sediment traps were located in 3 ephemeral subwatersheds within 8 of the original 16 SMZ treatment watersheds to provide 8 replications of 3 subwatershed treatments (Figures 1 and 2).

Within each of the 8 watersheds, 3 well-defined ephemeral subwatersheds were selected that included the range of operational disturbances and allowed sediment trap installation. The selected subwatersheds had a defined area of convergence and evidence of channelized scouring and the subwatershed stream slopes ranged between 5 and 28%. These convergent ephemeral watersheds were selected because divergent ephemeral watersheds have been reported to produce little sediment to a defined outlet (Bren 2000). Within each of the 8 selected SMZ treatment watersheds 3 sediment traps were installed to evaluate the sources of sediment to the SMZ, which resulted in a total of 24 ephemeral subwatersheds. The sediment traps were constructed with commercially available geotextile fabric and wooden stakes, similar to the design described by Robichaud and Brown (2002) and Rivenbark and Jackson (2004). All SMZs had bladed firelines positioned immediately adjacent to the SMZ as protection from wildfires. In each of the 8 selected watersheds, one of the three sediment traps was positioned in one subwatershed up-slope of the fireline. This sediment trap collected sediment from the clearcut, which included the harvest-site prepared areas, roads, skid trails, and decks (clearcut treatment). The second sediment trap was positioned in the second subwatershed between the fireline and the SMZ. This sediment trap captured sediment from the combination of the clearcut and fireline (fireline treatment). The sediment trap in the third ephemeral subwatershed was at the stream bank within the SMZ (SMZ treatment). The SMZ sediment trap captured sediment from all up-slope operations in the subwatershed that was delivered to the stream bank (Figure 1). The replication of the 3 subwatershed treatments (clearcut, fireline, and SMZ) within each of the 8 watersheds (24 subwatersheds) allowed evaluation of the sediment contribution of the clearcut harvest, including roads, decks, and skid trails (clearcut), the fireline and clearcut contributions (fireline), and the sediments from the clearcut and fireline that penetrated the SMZ (SMZ). Subwatershed data were analyzed as a randomized complete block design having 8 blocks (watersheds) and 3 treatments (clearcut, fireline, and SMZ) per block for a total of 24 experimental subwatershed units.

Erosion delivery estimates were calculated based on both the 16 larger watersheds and the 24 subwatersheds. The technique is similar to that of Ward and Jackson (2004), who calculated the ratio of trapped sediment relative to USLE-Forest Version modeled erosion. For the larger watersheds, the USLE-Forest Version modeled erosion to sediment pin ratios were calculated; for the subwatersheds, modeled erosion to sediment trap ratios were calculated.

Watershed data for the 16 watersheds were analyzed using the mixed model for the incomplete block design with Statistical Analysis System (version 9.2; SAS, Research Triangle Park, NC). Data from the 24 ephemeral subwatersheds used the mixed-model procedures for the randomized complete block design (SAS). When significant treatment differences were detected, Tukey-Kramer adjusted mean separation tests were used to determine significance between treatment means and transect means at the 0.05 α level.

Results and Discussion

Watershed, harvest, and bare soil areas as well as stream outlet width and stream slopes for the 16 watersheds are provided in Table 1. Analyses of variance revealed no significant differences between areas of harvest and site preparation, decks, skid trails, roads, and firelines between the watersheds. As SMZ width increased, average watershed percentages included within the SMZ averaged 1.9, 6.3, and 11.8% for the 7.6-, 15.2-, and 30.4-m-wide SMZs, respectively. These averages vary from theoretical averages because SMZ widths were seldom exact and often contained additional branches due to stream drainage patterns. The area of each operation (Table 2) was multiplied by the USLE-Forest Version erosion estimate (Table 3) to provide the total estimated erosion within an operational category and watershed (Table 4).

Table 2. Average areas of harvest site preparation, decks, roads, skid trails, firelines, streamside management zones (SMZ), and total watershed by SMZ treatment

Watershed operational categories	Treatments				Probability values
	7.6m SMZ ($n = 3$)	15.2m SMZ THIN ($n = 3$)	15.2m SMZ ($n = 7$)	30.4m SMZ ($n = 3$)	
	........(ha)........				
Harvest site preparation	43.0	21.3	25.3	18.5	0.5733
SMZ	0.8	2.9	1.6	2.2	0.6741
Deck	0.1	0.1	0.1	0.1	0.5907
Skid trails	0.8	0.5	0.5	0.4	0.3765
Roads	0.3	0.3	0.4	0.2	0.2934
Fireline	0.2	0.4	0.4	0.2	0.2518
Watershed	45.2	25.5	28.3	21.6	0.6605

Probability values indicate the probability that the watershed operational categories within the SMZ treatments are similar to one another.

Table 3. Average annual erosion rates estimated with the Universal Soil Loss Equation-Forest Version for harvest site preparation, decks, roads, skid trails, firelines, streamside management zones (SMZs), and total watershed by SMZ treatment during the 1st year after operations

Watershed operational categories	Treatments 7.6m SMZ ($n = 3$)	 15.2m SMZ THIN ($n = 3$)	 15.2m SMZ ($n = 7$)	 30.4m SMZ ($n = 3$)	Probability value
	........(tonnes ha^{-1} yr^{-1})........				
Harvest site preparation*	7.1	12.2	8.6	15.6	0.6669
Deck*	2.9	5.4	8.0	12.1	0.1538
Skid trails*	8.6	11.0	30.2	38.0	0.4803
Roads*	43.0	69.2	49.4	86.1	0.2911
Fireline*	74.2	122.4	198.8	43.3	0.5857
Watershed	7.5	13.2	11.7	15.3	0.4838

Probability values indicate the probability that the SMZ treatments are similar to one another regarding erosion within the operational categories.
* 5–7 Universal Soil Loss Equation-Forest Version subsamples were conducted for each watershed disturbance category.

Table 4. Total predicted erosion rates as estimated with the Universal Soil Loss Equation-Forest Version for harvest site preparation, decks, roads, skid trails, firelines, streamside management zones (SMZ), and total watershed by SMZ treatment during the 1st year after operations

Watershed disturbance categories	Treatments 7.6m SMZ ($n = 3$)	 15.2m SMZ THIN ($n = 3$)	 15.2m SMZ ($n = 7$)	 30.4m SMZ ($n = 3$)	Probability value
	........(tonnes yr^{-1})........				
Harvest site preparation	305.3	259.9	217.6	288.6	0.8569
Deck*	0.3	0.5	0.8	1.2	0.4978
Skid trails*	6.9	5.5	15.5	15.2	0.6811
Roads*	12.9	20.8	19.8	17.2	0.8266
Fireline*	14.8	49.0	79.5	8.7	0.7041
Watershed	340.2	335.6	333.2	330.9	0.8972

Probability values indicate the probability that the SMZ treatments are similar to one another regarding erosion within the operational categories.
* 5–7 Universal Soil Loss Equation-Forest Version subsamples were conducted for each watershed disturbance.

The average combination of decks, roads, skid trails, and firelines comprised 1.5% of the total area within all watersheds (Table 1), yet produced 16.5% of the total estimated erosion (Table 4). Decks were the disturbance category that produced the least erosion (<1%) because of the combination of small areas, location on gentle terrain, and closure with seeding. Roads produced significant erosion on a per area basis (Table 3), but their small area reduced the total effect and resulted in 5.3% of the total estimated erosion. Skid trails contained more than twice as much area as roads, but sediment contributions were only 3.2% of the total estimated erosion in watersheds. Although skid trails have much lower standards than roads (e.g., trail grades were steeper), skid trails were closed with water bars, seeded after harvest, and quickly grew vegetative cover. Firelines, which were constructed with a dozer blade in a fashion similar to that for bladed skid trails, yet with less regard to slope, averaged 11.3% of the total watershed estimated erosion. The combination of harvesting and prescribed burning site preparation comprised an average of 76% of the area and 80% of the predicted erosion.

Pre- and postharvest sediment pin data indicated that sediment trapped within SMZs was not significantly different for the four SMZ treatments (Table 5). However, significant increases in sediment as indicated by erosion pins, occurred between pre- and postharvest conditions within all

Table 5. Average streamside management zones (SMZ) area, erosion trapped, and sediment/erosion ratio in the four SMZ treatments based on sediment pin data (36 erosion pins per watershed)

Watershed disturbance categories	Treatment 7.6m SMZ ($n = 3$)	 15.2m SMZ THIN ($n = 3$)	 15.2m SMZ ($n = 7$)	 30.4m SMZ ($n = 3$)	Probability value
SMZ area (ha)	0.8	2.9	1.6	2.2	0.6741
Preharvest SMZ sediment (tonnes ha^{-1} yr^{-1})*	0.67	0.65	0.64	0.67	0.9560
Postharvest SMZ sediment (tonnes ha^{-1} yr^{-1})*	25.9	26.4	19.6	27.4	0.9149
Sediment pin: USLE-Forest Version erosion estimate ratio	0.08	0.08	0.06	0.08	0.9766

Probability values indicate the probability that the SMZ treatments are similar to one another.
* Each watershed had 36 sediment pins installed in the SMZ (3 transects × 12 pins).
USLE, Universal Soil Loss Equation.

treatments, indicating that SMZs were necessary for trapping sediment related to the disturbances. Pretreatment sediment pins indicated that SMZs were trapping an average of 0.65 tonnes ha^{-1} $year^{-1}$. After treatment installations, sediment pin data indicated that SMZs were collecting an average of 24.8 tonnes ha^{-1} $year^{-1}$, which amounts to a 38× increase. No significant differences in sediment pin data between or within the transects were detected so the sediment pin data within a given watershed were simply averaged.

The erosion/sediment delivery ratios were calculated for entire watersheds by comparing the USLE-Forest Version predicted erosion with the sediment pin data collected in the SMZs (Table 5). Expressing the erosion/delivery ratios as a percentage, the 7.6m SMZ, 15.2m SMZ, 15.2m SMZ THIN, and 30.4m SMZ treatments had erosion/sediment delivery ratios of 7.6, 7.8, 5.8, and 8.3%, respectively. For comparison, Ward and Jackson (2004) found erosion/sediment delivery ratios of 25% for Georgia Piedmont sites that were chemically site prepared and mechanically treated with a Savanna plow, a disturbance that was more disruptive than that used for this study. The wider SMZ treatments were originally expected to be more effective than the narrower treatments for trapping sediment, but analyses failed to detect any significant differences. The lack of significant differences may relate to the shape of the floodplain and associated uplands. The wider SMZs contain the relatively gentle floodplain near the streams plus the steeper sideslopes (up to 65%), whereas the more narrow SMZ treatments were primarily restricted to the gentle floodplain. These SMZ shapes are common for headwater streams across the Piedmont region (Fenneman 1938). However, the sediment pin data did not reveal any significant differences in sediment deposition across the SMZ transect. All SMZs had intact litter layers and were similarly effective for trapping sediment.

For the smaller subwatersheds, sediment volumes (m^3) collected by the sediment traps were calculated based on sediment depth and area. Next, tonnes of sediment were obtained by multiplying volumes (m^3) by soil bulk density values (tonnes m^{-3}). The 24 subwatersheds were an order of magnitude smaller than the original 16 watersheds (Table 6), yet they reflected similar terrain, site, operational, and vegetative features. For the subwatershed sediment trap data, significant differences were not detected for the original SMZ width treatments ($P = 0.5439$) nor for the interaction of SMZ width treatments × subwatershed treatments ($P = 0.6508$). However, significant differences were found between the sediment trapped from the harvest, fireline, and SMZ treatments for the subwatersheds ($P = 0.0342$). This secondary study allowed examination of the disturbance locations and the contribution to sediment movement from the disturbances. For example, the firelines were located between the harvest area and the SMZ treatments. Subwatershed data indicate that the fireline contributed approximately 12 times more sediment per unit area than the harvest, which included roads, decks, and skid trails. These findings indicate that bare soil (i.e., high erosion potential) disturbances that are closer to the SMZ may contribute a disproportionate quantity of sediment, as was found by Swift (1986) and Megahan and Ketcheson (1996).

Sediment volumes collected by traps within each of the subwatersheds were also compared with the erosion predicted by the USLE-Forest Version estimates to calculate the sediment delivery ratio. The fireline located immediately adjacent to the SMZs had a delivery ratio of 14%, which was double that of the harvest and site preparation disturbances. The sediment trap located at the stream had an average delivered sediment/watershed erosion ratio of 3%, indicating that an average of 97% of the eroded materials were trapped on-site within the harvest area or the SMZ before reaching the stream. Ward and Jackson (2004) found similar efficiencies (71–99%) for the Georgia Piedmont, although their mechanical site preparation treatments were more intensive.

These results also generally support those of Rivenbark and Jackson (2004), who found that SMZs could be overwhelmed by "blow through" areas caused by channelized flow of water and sediment through the SMZ. Their problems were primarily associated with the reactivation of agricultural erosion gullies by site preparation.

For this study, visual examinations indicated that significant scouring and minor channel formation occurred within 3 of the 24 minor subwatershed SMZs. For these subwatersheds, sediment was obviously bypassing the SMZ and entering the streams during rainfall events. For the 3 "problem" subwatersheds, sediment bypassed the SMZ regardless of SMZ width and the apparent causes were failed water control structures associated with road segments or firelines on steep slopes/fragile soils. Croke et al. (1999, 2001) found that forest roads and skid trails concentrated water an order of magnitude greater than harvested areas, which caused them to be more efficient in sediment delivery than simple timber harvests. For this study, the specific SMZ evasions were due to three specific and identifiable causes. First, a

Table 6. Sediment trapped and sediment/erosion ratio at the outlet in 3 subwatersheds in each of 8 larger watersheds

Subwatershed parameter	Sediment trap position: Harvest	Fireline	Streambank	Probability value
Average subwatershed area (ha)	1.1	0.9	1.2	0.6913
Sediment trapped (tonnes ha^{-1} yr^{-1})	7.6 a	15.2 b	10.1 ab	0.0342
Sediment trap: USLE-Forest Version erosion estimate ratio	0.07 b	0.14 c	0.03 a	0.0411

Each subwatershed represents harvest-related disturbances, firelines and harvested related disturbances, or the soil management zone at stream. Numbers followed by different letters are significantly different within a row.
USLE, Universal Soil Loss Equation.

road water turnout was installed too steeply so that it concentrated water on a fireline. Second, a ditch relief culvert concentrated flow from a road segment that was approximately four times the recommended length. Finally, a road ditch concentrated more than 400 m of ditch water into an ephemeral subwatershed that had a preexisting agricultural erosion gully. These BMP failures were still active during the second year after harvest and probably indicate that BMP successes on slopes and stream approaches are not guaranteed for long periods without inspection and maintenance. In addition, the common practice of pushing firelines around the SMZ and stream head to avoid crossing the SMZ with a fireline (Virginia Department of Forestry 2002) may actually increase the threat of sedimentation, rather than reduce it.

The quantities of accumulated sediment in the traps, even in the worst situation, were relatively minor compared with erosion rates associated with alternative land uses and were not indicative of a serious water quality problem as defined by the Virginia Silvicultural Water Quality Law (Public Law VA Code §10.1–1181.2). Lakel (2008) worked with these same watersheds for a chemical water quality study and found that the treatments did not differ with regard to several water quality parameters, including nitrogen, phosphorus, suspended sediment concentrations, turbidity, and total dissolved solids. Water quality was above state and federal standards in all watersheds studied, and water quality did not change significantly with SMZ width (Lakel et al. 2006a, Lakel 2008).

The data are also in general agreement with other related erosion/SMZ research. Carroll et al. (2004) found that sediment depositions in riparian zones were not affected by SMZ or harvest treatment and did not differ by distance from the stream or landscape position. Measured deposition ranged from 0.1 to 0.4 cm, and no treatments showed a net loss of sediment. Their study determined that sediment deposition in riparian areas was an ongoing natural process that was not noticeably affected by harvesting in general regardless of SMZ treatments. Keim and Schoenholtz (1999) also found that sediment deposition in the Mississippi Loess Hills region ranged from 0.2 to 2.0 cm over a 3-year postharvest study period. The presence of an SMZ (thinned or not) or the complete lack of an SMZ had no impact on sediment deposition in the riparian areas. In their study, it appeared that the maintenance of an SMZ to encourage deposition or decrease erosion was simply unnecessary. Their study also indicated that distance from the stream had no significant impact on sediment deposition or soil erosion. These previous studies were very similar to this study in purpose, design, and result. As with these data, the most important results were that wider SMZs did not have significantly higher sediment deposition rates than narrow ones. Overall, these studies indicate that maintaining forest floor integrity, regardless of partial canopy removal, reduces water velocity and increases sediment trapping. Sheridan et al. (1999) also found that forested buffers could be managed for financial gain through commercial thinning and clearcutting while still maintaining their sediment-filtering functions.

Wynn et al. (2000) also monitored water quality in several watersheds in the coastal plain of Virginia and found that BMP worked well to limit total suspended sediment in stream water after harvesting and site preparation. However, their study did not determine whether elevated total suspended sediment values in the no-BMP watershed were due to any deficiencies in SMZ maintenance or proper road stabilization. They study concluded that the elevated sediment values in the no-BMP watersheds might have been due to the lack of water control structures on roads and decks.

SMZ width and efficacy are important for water quality, but SMZ widths also have important implications for landowners with regard to financial returns and logistical considerations. Bren (1995) found that wider SMZs can effectively entrap other management areas, thus reducing management options. In addition, the extension of a 7.6-m SMZ to 15.2 m could theoretically increase SMZ area by 0.75 ha km^{-1} (per side of stream), and SMZ area would be increased by 1.5 ha km^{-1} of SMZ by extending a 15.2-m SMZ to 30.4 m. This extension could easily account for as much as 3 ha km^{-1} of SMZ removed from future harvests, which could affect financial returns to landowners (Shaffer and Aust 1993, Shaffer et al. 1998, Kluender et al. 2000, Cubbage 2004, Lakel et al. 2006b, LeDoux 2006). Estimates of monetary loss will vary greatly, depending on length or area of SMZ, timber quality, tax implications, stumpage values, and volumes. SMZ width recommendations vary, and recommendations often imply that wider SMZs are better for prevention of sedimentation (Blinn and Kilgore 2001), but the soil erosion data and the accumulated sediment data of this study (Tables 4 and 5) suggest that wider SMZs may not be necessary for prevention of sedimentation from forest operations in the Piedmont. The cost of increasing SMZ width is borne by landowners, and these data indicate that the current recommendation of 15.2-m SMZs with or without partial harvests provide adequate sediment trapping capacity for typical forest harvest and site preparation operations in the Piedmont region of Virginia. However, wider SMZs may be necessary for more erosive land uses, in situations in which water pollutants other than sediment are a major concern, BMP compliance is low, or wider SMZs are selected because of additional landowner or societal goals.

Conclusions

The USLE-Forest Version erosion estimates indicated that forest harvesting increased soil erosion in watersheds, yet the sediment pin and sediment trap data indicate that little of this erosion actually entered the stream because of the effectiveness of on-site and within SMZ sediment trapping. Wider SMZs were not superior with respect to sediment trapping and on-site observations indicate this may be due to the steeper terrain associated with a portion of the wider SMZs. The data also support thinning within SMZs as an appropriate forest management tool, because the practice did not significantly increase erosion. Some states and agencies have recommended that wider SMZs be left when timber is harvested within SMZs (Blinn and Kilgore 2001). However, our data indicate that the relatively narrow SMZs were as effective in protecting streams from sediment additions as were the larger SMZs. Data also indicate that the proximity of the disturbance to the SMZ may be as important as the degree of disturbance. Firelines had erosion rates as great as road and skid trails, yet the fireline contributed a disproportionately greater percentage of the sediment to the SMZ. It is important to note that the disturbance treatments were those normally associated with harvesting and site preparation and do not represent SMZ needs for more potentially erosive disturbances as might be associated with agricultural uses or conversions, construction activities, or suburban development activities. Such activities could contribute larger volumes of sediment and might necessitate wider SMZs and additional BMP.

These data should not be used to discourage the use of wider SMZs in situations in which professional judgment or site conditions indicate their utility. These findings promote understanding of SMZ sediment trapping functions in the Piedmont and interpret circumstances in which these functions best occur. The three "SMZ failure" subwatersheds are not sufficient for major conclusions, yet they emphasize that road water control problems can allow sediment to pass through the SMZ. This research suggests that areas of concentrated flow can lead to SMZ failures where sediment is more likely to reach stream channels. In conclusion, the presence of an SMZ of even minimal width is a BMP that should be included in harvest planning.

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