Efficiencies of Forestry Best Management Practices for Reducing Sediment and Nutrient Losses in the Eastern United States

Pamela J. Edwards and Karl W.J. Williard

ABSTRACT

Quantifying the effects of forestry best management practices (BMPs) on sediment and nutrient loads is a critical need. Through an exhaustive literature search, three paired forested watershed studies in the eastern United States were found that permitted the calculation of BMP efficiencies—the percent reduction in sediment or nutrients achieved by BMPs. For sediment, BMP efficiencies ranged from 53 to 94% during harvest and up to 1 year after harvesting. For nutrients, BMP efficiencies were higher for total nitrogen (60–80%) and phosphorus (85–86%), which included particulate and sediment-bound forms, than for nitrate-nitrogen (12%), which occurs primarily in the dissolved phase. Results indicate forestry BMPs can significantly reduce sediment and nutrient loads; however, BMPs appear to be more effective at reducing pollutants associated with surface runoff than with subsurface flow.

Keywords: harvesting, nitrogen, paired watersheds, phosphorus, water quality

A multitude of studies have been published that have compared sediment or nutrient loads from undisturbed and managed watersheds in which forestry best management practices (BMPs) have been used (Aubertin and Patric 1974, Hornbeck et al. 1986, Lynch and Corbett 1990, Martin et al. 2000, Swank et al. 2001, Macdonald et al. 2003, McBroom et al. 2008) to estimate the effects of management on water quality. The findings have been relatively consistent, showing that both the magnitude and the duration of effects on water quality due to forest management are quite limited as long as BMPs are fully and properly used. Ironically, only a very few studies have directly measured the effectiveness of individual BMPs (e.g., Trimble and Sartz 1957, Reinhart and Eschner 1962). However, based on paired watershed studies and the fact that most BMPs are based on the laws of physics (Stuart and Edwards 2006), BMPs are generally accepted as being capable of protecting water quality.

To gain a better understanding about the effectiveness of forestry BMPs in the eastern United States, we have calculated BMP efficiencies from the available, small subset of paired watershed studies, in which one watershed was harvested with BMPs and the second was harvested without BMPs. Thus, efficiency is the percent reduction in sediment or a nutrient achieved by using BMPs. Sediment and nutrient reductions were based on in-stream water-column loadings because, presently, there are no published studies/measurements that have measured and compared hillside delivery of sediment or nutrients from harvesting with and without BMPs. In this analysis, nutrients are restricted to nitrogen and phosphorus, since these are the nutrients of most concern associated with forest operations.

Methods

The data used to calculate sediment and nutrient reductions were extracted from the articles listed in Table 1. Associated data used for calculating the sediment and nutrient BMP efficiencies are shown in Tables 2 and 3, respectively. The study by Kochenderfer and Hornbeck (1999) is not a conven-

Received November 19, 2008; accepted September 8, 2009.

Pamela J. Edwards (pjedwards@fs.fed.us) is research hydrologist, US Forest Service, Northern Research Station, PO Box 404, Parsons, WV 26287. Karl W.J. Williard (williard@siu.edu) is professor, Forest Hydrology, Forestry Department, Southern Illinois University, Carbondale, IL.

Table 1. Studies from which sediment and nutrient data were obtained for calculating forestry best management practices (BMPs) efficiencies.

Reference	Treatment/watershed description	Location	Constituents measured
Kochenderfer and Hornbeck (1999)	One watershed (38.8 ha) diameter limit cut to 35.6-cm dbh with BMPs, one watershed (29.9 ha) clearcut to 12.7-cm dbh without BMPs; hillside slopes averaged 40% in both watersheds	Allegheny Plateau, north central West Virginia	Sediment
Wynn et al. (2000)	One watershed (8.5 ha) clearcut with BMPs, one watershed (7.9 ha) clearcut without BMPs; fire lines installed, herbicide applied, controlled burn and hand planting followed; hillside slopes averaged 2% over most of harvested areas, except up to 30% slope along deeply incised streams	Coastal Plain, Virginia	Sediment, nitrogen, phosphorus
Arthur et al. (1998)	One watershed clearcut with BMPs, one watershed clearcut without BMPs; watershed areas not given; on both watersheds, commercial sawtimber logs >35.5-cm dbh were cut and removed and all stems <5-cm dbh were cut and left on site; hillside slopes averaged 45%.	Cumberland Plateau, eastern Kentucky	Sediment, nitrogen, phosphorus

tional paired watershed study, because the harvest without BMPs occurred approximately 30 years before the harvest with BMPs, but it is included in this analysis because of the lack of available data of this type. The difference in timing of the harvesting without and with BMPs may have affected the results, but the study periods were relatively comparable so the effects on the results may be small. Both harvests were completed during years of about average precipitation and number of significant precipitation events, and precipitation over the next several years was well below average in both cases (US Forest Service, unpublished data, 1999). In addition, both harvested watersheds had the same soil series and average hillside slopes.

For each of the studies, percent efficiency for each year or time period of available data was calculated from

$$\%\text{Efficiency} = \frac{\text{no BMPs} - \text{with BMPs}}{\text{no BMPs}} * 100$$

where no BMPs is the load measured from the watershed in which BMPs were not used, and with BMPs is the sediment or nutrient load measured from the watershed in which BMPs were used.

In the United States, forestry BMPs can be either mandatory under applicable state laws or voluntary, depending on the state. Of the three states included in this study, both West Virginia and Kentucky have mandatory BMPs (Stringer and Perkins 2001, West Virginia Division of Forestry 2005). However, the Arthur et al. (1998) study was completed before forestry BMPs becoming mandatory in Kentucky via the 1998 Kentucky Forest Conservation Act (Stringer and Perkins 2001). The state of Virginia has voluntary forestry BMPs except for practices associated with road construction and maintenance, which are mandatory (Virginia Department of Forestry 2002).

Results and Discussion

Sediment

Even though the studies by Kochenderfer and Hornbeck (1999) and Wynn et al. (2000) were performed in very different physiographic regions (Table 1) with different topographic conditions, similar high BMP efficiency values for sediment were achieved during approximately the first 6 or 12 months after harvesting (Table 2). These efficiencies of 96 and 94%, respectively, are in contrast to much smaller values obtained by Arthur et al. (1998) in Kentucky (Table 2). During the year of harvesting, the BMP efficiency for sediment was only 53%, which then declined to 34% during the first approximate 1.5 years after harvesting (Table 2). However, Arthur and her colleagues noted that sediment increases resulting from harvesting in the watershed without BMPs probably would have been greater had their logging crew not been well trained in BMPs; their crew used BMPs in some instances even though they were not required to do so. For example, their crews never skidded logs downhill, even though this is a common practice when BMPs are ignored (e.g., Reinhart et al. 1963, Kochenderfer and Hornbeck 1999). If no BMPs had been used, the actual BMP efficiency presumably would have been higher than 53%.

In the two studies involving harvesting alone, BMP efficiencies declined quickly after harvesting. In West Virginia, the 2nd year postharvest efficiency dropped about 20 percentage points to 76%, and in Kentucky sediment exports from the paired watersheds were approximately equal within 2.5 years of harvesting, so the BMP efficiency was effectively zero (Table 2). Over time, the actual reductions in sediment loads were much greater in the Kentucky watershed in which no BMPs were used compared with the one in which they were used (Table 2). That was probably because sediment loads in the former watershed were initially elevated more by the disturbance. By water year 1988 (approximately 4.5 years after harvest), the BMP efficiencies became more erratic (ranging from −94 to 53%), suggesting that the variations were then being influenced by conditions other than residual harvest effects.

BMP efficiencies remained high (Table 2) when site preparation activities occurred 7 months after harvesting (Wynn et al. 2000). Respective soil losses were approximately the same after site preparation as they were after harvesting on both of the watersheds harvested with and without BMPs (Table 2). However, stormflow volumes unexpectedly decreased below predicted levels after both harvesting and site preparation on the no-BMP watershed (Wynn et al. 2000), which acted to control the calculated sediment loads during those periods. Because the streamflow component comprises a substantial portion of the sediment load value and the majority of sediment is exported during storm events (Beasley 1979, Edwards

Table 2. Sediment loads resulting from harvesting with and without best management practices (BMPs) and associated efficiencies (i.e., percent reduction) resulting from using forestry BMPs.

Reference	Time period	Sediment load: Without BMPs	Sediment load: With BMPs	Calculated efficiency (%)
Kochenderfer and Hornbeck (1999)	1st yr postharvest	3.23 Mg/ha	0.12 Mg/ha	96
	2nd yr postharvest	0.32 Mg/ha	0.08 Mg/ha	76
Wynn et al. (2000)	Postharvest (6 mo)	9.76 Mg/ha per yr	0.56 Mg/ha per yr	94
	Post–site preparation (14 mo)	7.67 Mg/ha per yr	0.62 Mg/ha per yr	91
Arthur et al. (1998)	During harvest (10 mo)	1.18 Mg/ha	0.55 Mg/ha	53
	1st 17 mo. Postharvest[a]	0.64 Mg/ha	0.42 Mg/ha	34
	Water year 1986[b]	0.38 Mg/ha	0.37 Mg/ha	2
	Water year 1988	0.10 Mg/ha	0.05 Mg/ha	53
	Water year 1989	0.20 Mg/ha	0.39 Mg/ha	−94
	Water year 1990	0.31 Mg/ha	0.07 Mg/ha	78

[a] Postharvest period ended October 1985.
[b] Water year 1986 began November 1985.

Table 3. Nutrient loads resulting from harvesting with and without best management practices (BMPs) and associated efficiencies (i.e., percent reduction) resulting from using forestry BMPs.

Nutrient/reference	Time period[a]	Nutrient load: Without BMPs (kg/ha per yr)	Nutrient load: With BMPs (kg/ha per yr)	Calculated efficiency (%)
Total nitrogen				
Wynn et al. (2000)	Postharvest (6 mo)	104.7	41.8	60
	Post–site preparation (14 mo)	85.4	17.1	80
Nitrate–nitrogen				
Arthur et al. (1998)	Postharvest (17 mo)	1.45	1.27	12
Total phosphorus				
Wynn et al. (2000)	Postharvest (6 mo)	12.61	1.72	86
	Post–site preparation (14 mo)	10.82	1.60	85
Phosphate–phosphorus				
Arthur et al. (1998)	Postharvest (17 mo)	0.38	0.21	45

[a] Loading values were adjusted to a per year basis for each of these time periods if not already expressed that way in the original reference.

and Owens 1991, Kochenderfer and Edwards 1991), without this hydrologic change, sediment exports on the no-BMP watershed may have been greater, and possibly much greater. This change would have increased the BMP efficiencies even more.

Because no data are available beyond 14 months after site preparation, it is not possible to determine how quickly BMP efficiencies would have declined on these watersheds. But based on the speed of recovery after only harvest at the other sites, one would expect a similar rapid decline in the efficiencies after site preparation. This is particularly true because the watershed hydrology of the no-BMP watershed apparently was tempered by the harvesting and site preparation activities.

Nutrients

Only the studies by Arthur et al. (1998) and Wynn et al. (2000) directly measured nutrient reductions attributable to BMP implementation. They monitored responses of phosphorus and nitrogen compounds, because these are the nonpoint source nutrients that most commonly limit primary production in freshwater ecosystems (Carpenter et al. 1998). The studies focused on different forms of phosphorus and nitrogen, and because they behave differently based on their chemical affinities to bond or dissolve, the different forms are described individually.

Total Phosphorus and Phosphate-Phosphorus. Total phosphorus includes all orthophosphates and condensed phosphates that exist in dissolved and particulate and organic and inorganic forms. Most phosphorus is transported as particulates bound to sediment. Thus, the efficiencies for total phosphorus should approach those for sediment; and, indeed, the efficiencies calculated from the Wynn et al. (2000) study were 86% after harvesting and 85% after site preparation (Table 3), which are similar to the 94 and 91% efficiencies for sediment for the respective periods (Table 2). The study by Arthur et al. (1998) in Kentucky resulted in a BMP efficiency for phosphate-phosphorus of 45% (Table 3). This analysis was performed using a spectrophotometer, so the values pertain only to the inorganic fraction. The analyses were performed on unfiltered samples (Dr. Mary Arthur, pers. comm., University of Kentucky, September 2008), which would suggest that much of the phosphorus would have been bound to sediment. The phosphorus efficiencies supported this, in that they are similar to the sediment efficiencies that year (Table 2).

Total Nitrogen and Nitrate-Nitrogen. Wynn et al. (2000) examined total nitrogen, which they defined as the sum of total Kjeldahl nitrogen (TKN) and ammonium. TKN is a measure of organic nitrogen compounds and ammonium. BMP efficiencies for total nitrogen calculated by the data reported by Wynn et al. (2000) were 60% 6 months after harvesting alone but increased to 80% during the 14 months after site preparation (Table 3). The increase after site preparation may have been caused by increases in in-stream particulate matter levels resulting from the herbicide and controlled burning (Table 1). In disturbed forested watersheds, streams can export significant amounts of particulate organic matter (Webster and Swank 1985). Because the excess organic matter associated with the harvest was treated with herbicides and it and the slash then were combusted during site preparation, the sources of organic nitrogen would have been removed quickly. Thus, the total nitrogen levels may have returned to preharvest levels more quickly than if harvesting had been performed without subsequent site preparation. Consequently, BMP efficiencies would have declined rapidly after site preparation was completed.

Nitrate is the dominant inorganic nitrogen species that leaches from soils to receiving waters. It is considered a mobile anion because of its exclusive nonspecific adsorption characteristics (Bohn et al. 1985) and it exists primarily in dissolved form. Nitrate leaching can increase after timber harvesting because of loss of vegetative uptake of nitrogen and enhanced microbial nitrification rates because of increased soil moisture, temperature, and physical disturbance (Vitousek and Melillo 1979, Huttl and Schaaf 1995). Most harvesting studies showed short-term increases in stream nitrate, with nitrate exports returning to preharvest levels in 3–4 years because of uptake by regrowing vegetation and soil nitrification returning to predisturbance rates (Hornbeck et al. 1986, Lynch and Corbett 1991, Pardo et al. 1995).

Arthur et al. (1998) found nearly identical nitrate exports with and without BMPs after harvesting (Table 3). As a result, the BMP efficiency for nitrate-nitrogen was only 12%. If the logging crew had not been as careful as they were on the watershed harvested without BMP, this efficiency may have been slightly higher. However, most forestry BMPs were developed to control surface water movement and energy; they were not intended to affect subsurface processes, other than to encourage infiltration of surface flows to the extent possible. Thus, because dissolved nutrients, such as nitrate, commonly travel by subsurface pathways, BMPs would not be expected to have a substantial influence on them, and lower efficiencies would be expected.

Streamside management zones or riparian buffers are important BMPs that can significantly affect dissolved nutrient losses. Depending on their characteristics, including slope, width, the species and density of vegetation present, soil characteristics, and hydrologic characteristics, riparian buffers have varying degrees of success in attenuating nutrients before surface runoff, soil water, and groundwater are discharged to streams. In the Kentucky study (Arthur et al. 1998), a 15.2-m-wide riparian buffer was used on each side of the stream in the watershed harvested with BMPs compared with no buffer in the no-BMP watershed. Given the low BMP efficiency for nitrate-nitrogen, wider buffers may be warranted to improve nitrate attenuation on these steep slopes, although buffer width may not be the most important factor in determining buffer effectiveness. A recent study in the upper piedmont of Virginia showed that narrow streamside management zones (7.6 m) are just as effective at protecting water quality than 15- or 30-m-wide buffers (Lakel et al. 2006). In the Georgia piedmont, Rivenbark and Jackson (2004) found that the presence of concentrated flow paths were more important in determining streamside management zone effectiveness than buffer width. Also, the annual nitrate-nitrogen export even with no BMPs (Arthur et al. 1998) was within the moderate range (1.0–2.0 kg ha^{-1} per year) of undisturbed forested watersheds in the mid-Appalachian region (Williard et al. 1997). Thus, there is probably little justification solely from a nitrate loss perspective to increase buffer widths.

Adjustments to Efficiency Values

The efficiencies presented here provide an indication of the reductions in sediment and nutrients that can be expected by proper and full implementation of forestry BMPs. However, one should use care in applying these specific values, even if the region to which they are applied is the one in which they were developed. Obvious variability in characteristics that exist among watersheds may result in different sediment and nutrient transport and, therefore, calculated BMP efficiencies. In addition to those differences, other factors need to be considered because these efficiencies were obtained from in-stream concentrations at the mouth of their respective watersheds.

In-stream concentrations and subsequent loadings are indirect measures of actual BMP effectiveness (Edwards 2003). They do not provide measures of sediment or nutrient delivery to water bodies resulting from all BMPs applied to the harvest area. In-stream measurements ignore several spatial and temporal factors, especially those involving sediment delivery or chemical constituents for which transport largely depends on sediment transport, such as phosphorus.

Some eroded sediment originating from management activities may be stored on the hillside or in the channel during at least the time in which monitoring was performed. If the area of storage was a riparian buffer and if storage is permanent, then the attribution of the reduction of the constituent delivery is fully appropriate in the calculation of the BMP efficiency. If storage was not by the riparian buffer or it was not permanent, attributing the entire efficiency value to the BMPs is not fully appropriate. Because substantial amounts of sediment delivered to a stream channel can be stored for decades and perhaps longer before being flushed from the watershed (Trimble 1981, Reid 1982), sediment efficiencies may be greatly overestimated in some situations. Given this long-term sediment storage potential in the watershed, the source of in-stream sediment may be previous timber harvesting operations or agricultural activities (Jackson et al. 2005).

Sediment BMP efficiencies also may be overestimated or underestimated because of the types of flow conditions that occur during monitoring. Most suspended sediment exports occur during large or intense storm events (Beasley 1979, Edwards and Owens 1991), which occur infrequently and randomly. So, even if sediment is delivered to a channel and remains relatively available, it may not be flushed from the watershed during the period of stream water monitoring. This would result in an overestimate of a BMP efficiency because the temporary storage would be interpreted as better BMP effectiveness than actually occurred. Analogously, flushing that includes a disproportionate load of long-term stored sediments during one or more infrequent high flows that occurred during monitoring may be misinterpreted as poorer BMP efficiency than actually existed.

Finally, there must be a recognition that BMP effectiveness may change in the future, including well past the closeout of the management activity. Road or culvert washouts are not uncommon because of a lack of maintenance and can lead to large and chronic loadings of sediment and nutrients to water bodies. In this type of situation, water quality protection from high BMP effectiveness and efficiencies in the short term could be more than negated by the effects of BMP failure in the long-term.

Conclusion

Direct accounting of the impacts of BMPs on sediment and nutrient loads is an increasing need as our nation moves toward regulatory and modeling frameworks (e.g., total maximum daily loads and Chesapeake Bay Model) that rely on sediment and nutrient budgets. In three forested watersheds in the eastern United States, BMP implementation significantly reduced sediment loads and particulate- and sediment-bound nutrient loads compared with watersheds with no BMPs. BMPs reduced dissolved nutrients, such as nitrate, to a much lesser extent. This finding was somewhat expected, because BMP guidelines focus primarily on limiting sediment transport, which is the nonpoint source pollutant of primary concern in forested watersheds. BMP efficiencies for sediment generally decreased over time, as sediment loads from the watersheds harvested without BMPs decreased in subsequent postharvest years. The three paired watershed studies referenced in this metadata analysis measured sediment and nutrients only in-stream at the watershed outlet. There is significant need to determine the important sources of sediment and nutrients within watersheds to more effectively design appropriate BMPs. Also, these studies were designed to evaluate the impact of a suite of applied BMPs on water quality. Load-based water quality impacts of individual forest BMPs, such as streamside management zones, remain unknown at the watershed scale.

Literature Cited

Arthur, M.A., G.B. Coltharp, and D.L. Brown. 1998. Effects of best management practices on forest streamwater quality in eastern Kentucky. *J. Am. Water Resour. Assoc.* 34: 481–495.

Aubertin, G.M., and J.H. Patric. 1974. Water quality after clearcutting a small watershed in West Virginia. *J. Environ. Qual.* 3:243–249.

Beasley, R.S. 1979. Intensive site preparation and sediment losses on steep watersheds in the Gulf Coastal Plain. *Soil Sci. Soc. Am. J.* 43: 412–417.

Bohn, H., B. McNeal, and G. O'Connor. 1985. *Soil chemistry*, 2nd Ed. John Wiley & Sons, Inc., New York. 341 p.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Applic.* 8(3):559–568.

Edwards, P.J. 2003. Forestry best management practices: Where we've been, where we're going. P. 26–33 in *Proc. of 2003 Penn State forest resources issues conference, Forestry's role in integrated water management.* The Pennsylvania State University, University Park, PA.

Edwards, W.M., and L.B. Owens. 1991. Large storm effects on total soil erosion. *J. Soil Water Conserv.* 46:75–78.

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

Huttl, R.F., and W. Schaaf. 1995. Nutrient supply of forest soils in relation to management and site history. *Plant Soil* 168–169:31–41.

Jackson, C.R., J.K. Martin., D.S. Leigh, and L.T. West. 2005. A southeastern piedmont watershed sediment budget: Evidence for a multi-millennial agricultural legacy. *J. Soil Water Conserv.* 60:298–310.

Kochenderfer, J.N., and P.J. Edwards. 1991. Effectiveness of three streamside management practices in the central Appalachians. P. 688–700 in *Proc. of 6th biennial southern silvicultural research conf.* US For. Serv. Gen. Tech. Rep. SE-70.

Kochenderfer, J.N., and J.W. Hornbeck. 1999. Contrasting timber harvesting operations illustrate the value of BMPs. P. 128–136 in *Proc. of 12th Central hardwood forest conf.*, Stringer, J.W., and D.L. Loftis (eds.). US For. Serv. Gen. Tech. Rep. SRS-24.

Lakel, W.A., W.M. Aust, and C.A. Dolloff. 2006. Seeing the trees along the streamside: Forested streamside management zones are one of the more commonly recommended forestry best management practices for the protection of water quality. *J. Soil Water Conserv.* 61:22A–29A.

Lynch, J.A., and E.S. Corbett. 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. *Water Resour. Bull.* 26:41–52.

Lynch, J.A., and E.S. Corbett. 1991. Long-term implications of forest harvesting on nutrient cycling in central hardwood forests. P. 500–518 in *Proc. of 8th Central hardwoods conf.* US For. Serv. Gen. Tech. Rep. NE-148.

MacDonald, J.S., P.G. Beaudry, E.A. MacIsaac, and H.E. Herunter. 2003. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. *Can. J. For. Res.* 33:1397–1407.

Martin, C.W., J.W. Hornbeck, G.E. Likens, and D.C. Buso. 2000. Impacts of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. *Can. J. Fish. Aquat. Sci.* 57:19–29.

McBroom, M.W., R.S. Beasley, and M. Chang. 2008. Water quality effects of clearcut harvesting and forest fertilization with best management practices. *J. Environ. Qual.* 37: 114–124.

Pardo, L.H., C.T. Driscoll, and G.E. Likens. 1995. Patterns of nitrate loss from a chronosequence of clear-cut watersheds. *Water Air Soil Pollut.* 85:1659–1664.

Reid, L.M. 1982. Evaluating and mapping sources and temporary storage areas of sediment. P. 138–142 in *Proc. of Workshop on sediment budgets and routing in forested drainage basins*. US For. Serv. Gen. Tech. Rep. PNW-141.

Reinhart, K.G., and A.R. Eshner. 1962. Effect on streamflow of four different forest practices in the Allegheny Mountains. *J. Geophys. Res.* 67:2433–2445.

Reinhart, K.G., A.R. Eshner, and G.R. Trimble. 1963. *Effect on streamflow of four forest practices in the mountains of West Virginia.* US For. Serv. Res. Pap. NE-1. 79 p.

Rivenbark, B.L., and C.R. Jackson. 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern piedmont, USA. *J. Am. Water Resour. Assoc.* 40:1043–1052.

Stringer, J.W., and C. Perkins. 2001. *Kentucky forest practice guidelines for water quality management.* Coop. Ext. Serv. FOR-67, Univ. of Kentucky, Lexington, KY. 112 p.

Stuart, G.W., and P.J. Edwards. 2006. Concepts about forests and water. *North. J. Appl. For.* 23:11–19.

Swank, W.T., J.M. Vose, and K.J. Elliott. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *For. Ecol. Manag.* 143:163–178.

Trimble, G.R. Jr., and R.S. Sartz. 1957. How far from a stream should a logging road be located? *J. For.* 55(5):339–341.

Trimble, S.W. 1981. Changes in sediment storage in the Coon Creek Basin, Driftless Area, Wisconsin, 1853–1975. *Science* 214:181–183.

Virginia Department of Forestry. 2002. *Virginia's forestry best management practices for water quality.* Virginia Department of Forestry, Charlottesville, VA. 216 p.

Vitousek, P.M., and J.M. Melillo. 1979. Nitrate losses from disturbed forests: Patterns and mechanisms. *For. Sci.* 25(4):605–619.

Webster, J.R., and W.T. Swank. 1985. Within-stream factors affecting nutrient transport for forested and logged watersheds. P. 18–41 in *Proc. of Forestry and water quality: A mid-South symposium*, Blackmon, B.G. (ed.). University of Georgia Press, Athens, GA.

West Virginia Division of Forestry. 2005. *West Virginia silvicultural best management practices for controlling soil erosion and sedimentation from logging operations.* WVDOF-TR-05-3. West Virginia Division of Forestry, Charleston, WV. 31p.

Williard, K.W.J., D.R. DeWalle, P.J. Edwards, and R.R. Schnabel. 1997. Indicators of nitrate export from forested watersheds of the mid-Appalachians, United States of America. *Global Biogeochem. Cy.* 11(4):649–656.

Wynn, T.M., S. Mostaghimi, J.W. Frazee, P.W. McClellan, R.M. Shaffer, and W.M. Aust. 2000. Effects of forest harvesting best management practices on surface water quality in the Virginia Coastal Plain. *Trans. Am. Soc. Agric. Eng.* 43:927–936.