Logging in New England Need Not Cause Sedimentation of Streams

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ABSTRACT. *Erosion, sedimentation, and turbidity can be controlled during and after logging in New England forests by conscientiously following regulations and guidelines known as Best Management Practices (BMPs). This is demonstrated by comparing sediment yields and stream turbidities from cut and uncut watersheds at the Hubbard Brook Experimental Forest in central New Hampshire. Sediment yields from uncut forests average about 40 kg/ha/yr, but are highly variable from year to year and from watershed to watershed. Disturbances due to cutting and logging can increase sediment yields. For example, in the first year after a whole-tree clearcut at Hubbard Brook, sediment yields increased 10- to 30-fold over uncut watersheds. However, total yields after cutting and skidding were still small and did not greatly affect stream turbidity. North. J. Appl. For. 11(1):17–23.*

New England is fortunate in that most of the region's forest soils are not prone to erosion. Litter layers and organic horizons of the forest floor allow rain and snowmelt to rapidly infiltrate into the mineral soil, even under extreme rainfall intensities. Mineral soil horizons are mostly well-drained, coarse-textured, sandy loams with high infiltration capacities. As a result, erosion rates and sediment yields from undisturbed forests are among the lowest in the country (Patric 1976), and erosive overland flow seldom occurs (Patric et al. 1984, Pierce 1967). Megahan (1972) showed that average stream sediment concentrations were lowest in New England of 12 geographic regions of the United States. A reasonable long-term average erosion rate for undisturbed forests in this region seems to be about 30 to 40 kg/ha/yr (Bormann et al. 1974, Patric et al. 1984). One kg/ha/yr is roughly equivalent to 1 lb/ac/yr.

Whenever the structure of these forest soils is disturbed, there is a chance for erosion along with subsequent sedimentation of nearby streams. Disturbance of the forest floor may channelize water, which increases its velocity and its ability to carry sediment. One pass of a skidder may compress the soil and form a channel to carry water and sediment. Repeated passes on the main skid trail lead to compaction and soil disturbance, which, in turn, can lead to severe erosion and sedimentation. Improperly designed and installed stream crossings can be a source of sediment to streams. But the major cause of erosion and sediment is improperly designed landings and truck roads. Sedimentation and turbidity resulting from logging are the major forms of water quality degradation in forest streams of New England.

Forest research over the last 4 decades has produced guidelines to help loggers, foresters, and landowners harvest timber without causing unacceptable erosion and degradation of streamwater quality (Trimble and Sartz 1957, Univ. N.H. Coop. Ext. Serv. 1957, Haussman 1960). This research provided detailed guidelines for the location of truck roads and skid trails, including specifications for grades, slopes, distances from streams, and stream crossings. Also included were design standards and construction techniques for bridges, culverts, and drainage facilities, including waterbars and broadbased dips. Finally, the studies discussed retirement techniques including grooming, seeding and mulching of roads, trails, and landings (Kochenderfer 1970, Winkelaar 1971, Hartung and Kress 1977).

The purpose of this paper is to show that if these well-documented recommendations are followed carefully, harvesting of forest products even with mechanized whole-tree clearcutting need not lead to excessive erosion of forest soils and the subsequent sedimentation of streams.

Methods

The Hubbard Brook Experimental Forest, located in the White Mountains of central New Hampshire, is the primary site in New England for research on erosion, sedimentation, and turbidity from forestlands. Hubbard Brook was established in 1955 as a watershed management research station. Eight stream gages were established to measure streamflow from forested watersheds. The gages are sharp-crested, v-notch weirs. Each year the sediment that collects in the stilling basin behind the v-notch is measured, excavated, sampled, dried, and weighed. Oven-dry weights are then calculated for all of the sediment removed from the basin and extrapolated back over the watershed as mass of soil material lost per unit area. On the basis of intensive studies of dissolved solids and suspended sediment, Bormann et al. (1974)

suggested that an additional 2% should be added to these values to account for particulates that flowed over the notches during high flows, and that 25% should be added to account for suspended sediment. The data presented here do not include these additions. Annual precipitation and sedimentation values presented in this paper are on a water-year basis. The water-year at Hubbard Brook is from June 1 through May 31.

Watersheds 1 through 6 are a set of contiguous watersheds (Figure 1) with a south-facing aspect. They range in elevation from 450 to 800 m above sea level. Slopes average 20 to 30%; localized slopes as steep as 70% occur near ridge tops and streams. Precipitation averages 1400 mm/yr occurring at the rate of 2 storms per week. From mid-December until mid-April, precipitation occurs as snow and accumulates as a snow pack. Soils of the watershed are fine sandy loams classed as Typic or Lithic Haplorthods derived from coarse-textured glacial till. Common soil series are Marlow, Lyman, Peru, Hermon, and Monadnock. The characteristics of WS 101 are similar to the other 6 watersheds except that it ranges in elevation from 470 m to 595 m with maximum slopes less than 35%.

Watersheds (WS) 1, 3, and 6 (Figure 1) are uncut reference watersheds. They are forested with mature northern hardwoods that have not been logged since 1920.

WS 2 is a clearfelled watershed. All trees and shrubs on WS 2 were cut in December 1965, in the presence of a snowpack, so that even the falling trees did not disturb the forest floor. No wood products were removed, and there were no skid trails or truck roads in the watershed. The watershed was then treated with herbicides for 3 yr to suppress regeneration (Bormann et al. 1974).

WS 4 is a stripcut watershed. Before cutting, the watershed was surveyed into 49 strips, each 25 m wide, oriented from east to west roughly parallel to the contour. Every third strip was harvested in the autumn of 1970. The second series of every third strip was cut in autumn of 1972. The third set of strips was cut in 1974. As a stem-only commercial clearcut, all stems greater than 2.5 cm dbh were cut by chain saw, and the boles were skidded to roadside by articulated, rubber-tired, cable skidders. The branches and tops were left in the woods. The size and quantity of wood removed was at the discretion of the logger. Prior to 1975, sediment yield data from WS 4 were collected volumetrically. No samples were taken for volume to weight calculations. Since the cutting occurred during this period, only turbidity data are presented for this watershed.

WS 5 was subjected to a mechanized, whole-tree clearcut in the winter of 1983-84. Cutting began in October 1983 and was completed in May 1984. Skidding was not completed until June 1985. Trees were felled using a track-mounted, swing-to-tree, feller-buncher, and skidded tree-length including boles, branches, and tops with articulated, rubber-tired, cable skidders. There were no truck roads in the watershed. All trees greater than 5 cm dbh were felled, and trees greater than about 15 cm dbh were skidded. Ninety-six percent of the aboveground living biomass was removed during the logging.

WS 101 was clearcut as one block in the autumn of 1970. All stems greater than 2.5 cm dbh were cut with a chain saw. The branches and tops were left on the clearcut. The stems were skidded to roadside with rubber-tired cable skidders. The size and quantity of wood removed was at the discretion of the logger. WS 101 is ungaged; therefore, there are no

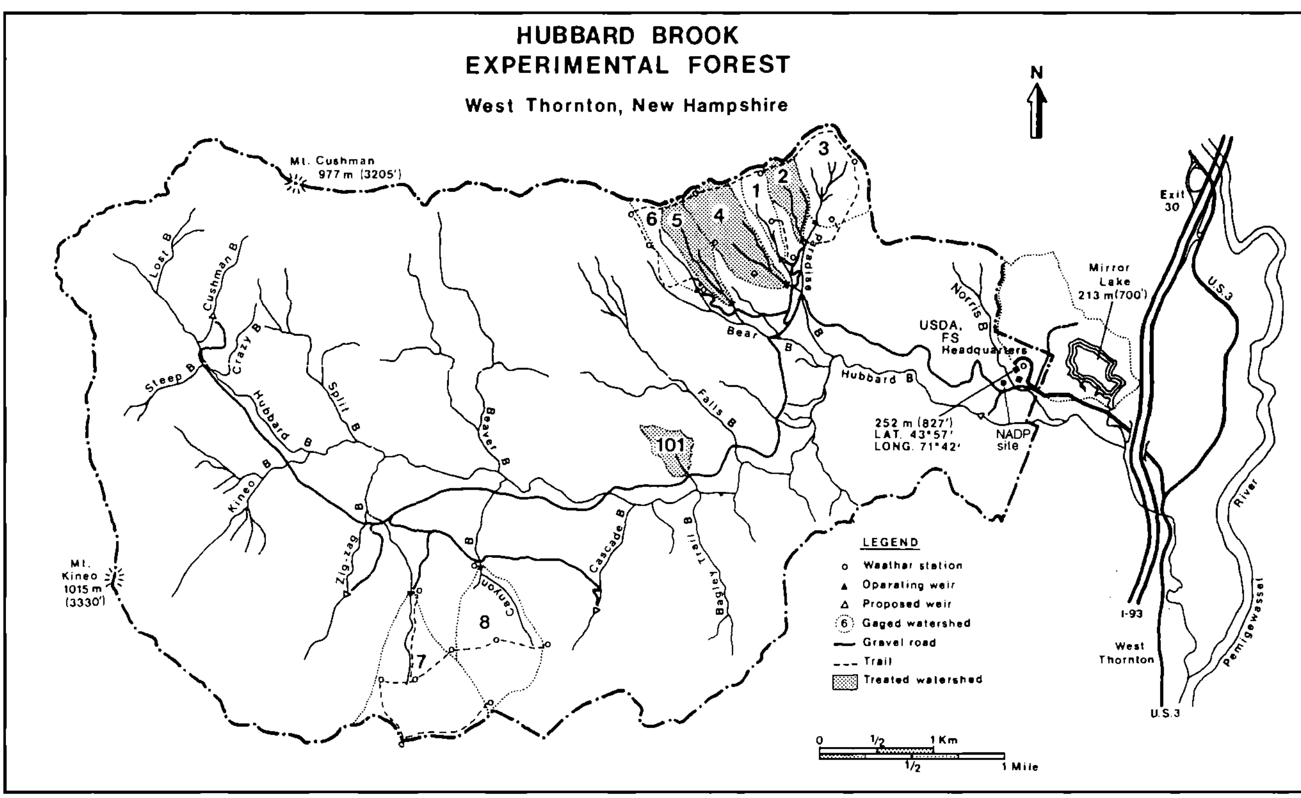

Figure 1. Map of the Hubbard Brook Experimental Forest.

sediment yield data, only turbidity data, for this watershed.

WS 4, 5, and 101 were logged commercially as part of the research program at Hubbard Brook. There were no truck roads on any of the watersheds. Skid trails were steep and occasionally exceeded 15% grade. However, while they ran up and down slope, they were located on the crest of the ridges between streams in the dryest sites with convex crowns to shed water. Broad-based dips were employed, and temporary water bars were installed as soon as the logger finished with a section of skid trail. Permanent water bars were installed, spaced according to percent slope, as soon as the skidding was complete. Culverts were required at all live stream crossings. A buffer strip of live trees was left on the main stream in WS 4 while a filter strip of undisturbed land was left along all streams. The trees were cut in the filter strips but were winched out with no equipment allowed near the streams. Logging slash was removed from the streams by the logger. Landings were located off the watersheds on dry convex sites. Petroleum and human waste were controlled. The operations were temporarily closed several times due to unfavorable weather. At the close of the sale, the landings were groomed and seeded.

Results and Discussion

Table 1 presents comparative sediment yields from three forested watersheds at Hubbard Brook that have not been logged since 1920. Average sediment yield from these watersheds is close to the predicted long-term average erosion rate of about 40 kg/ha/yr for undisturbed forests in this region (Patric et al. 1984).

Table 1. Comparative sediment yields from three undisturbed forested watersheds at the Hubbard Brook Experimental Forest in New Hampshire. Watershed (WS) 1 is 11.8 ha; WS 3 is 42.4 ha; WS 6 is 13.2 ha. All are drained by 1st- or 2nd-order streams. The last logging was prior to 1920.

Year	WS-1	WS-3	WS-6	Precip. (mm)
		(kg/ha)		
1975	68	35	18	1308
1976	20	10	15	1769
1977	62	29	79	1402
1978	131	37	18	1532
1979	61	47	25	1362
1980	141	64	32	1194
1981	41	25	34	1355
1982	47	28	10	1585
1983	10	11	3	1410
1984	84	47	35	1638
1985	7	5	4	1200
1986	52	45	17	1425
1987	108	71	52	1311
1988	6	4	1	1290
1989	18	19	7	1234
1990	13	24	13	1553
Mean	54	31	23	1411
SD	44	20	20	165
CV (%)	81	65	87	12

Several approaches were used in comparing sediment yields from the Hubbard Brook watersheds. For these undisturbed, forested watersheds, annual values for 16 yr are presented together with means, standard deviations, and coefficients of variation. The latter statistics illustrate the natural variability inherent in sediment data from forested watersheds.

Sediment yield from these contiguous watersheds was not related to watershed size. WS 1, the smallest at 11.8 ha, had the highest average yield at 54 kg/ha and consistently had higher sediment yields than the other two watersheds. WS 6, similar in area at 13.2 ha, had the lowest average sediment yield at 23 kg/ha. WS 3, the largest at 42.4 ha, had a yield of 31 kg/ha.

Sediment yields between the three watersheds were not well correlated. The best correlation for the 1975 through 1990 period was WS 1 and WS 3 with an r^2 of 0.849. WS 1 and WS 6 were poorly correlated with an $r^2$of 0.508; as were WS 3 and WS 6 at r^2 of 0.547. Also, there was considerable variation from year to year. Sediment yield from WS 1 ranged from 6 to 141 kg/ha with a coefficient of variation (CV) of 81%. WS 3 ranged from 4 to 71 kg/ha with a CV of 65%. WS 6 ranged from 1 to 79 kg/ha with a CV of 87%.

Sediment yield was not well correlated with annual precipitation amounts (Table 1). Correlation of sediment yield with annual precipitation gave r^2 values of 0.004, 0.013, and 0.000 for WS 1, WS 3, and WS 6, respectively. Sediment yields from all 3 watersheds were lowest in 1988, which was a dry year, but not the dryest year. In fact, the highest sediment yield for WS 1 occurred in 1980, the year with the lowest precipitation, and sediment yields from all 3 watersheds were below average in 1976, the year with the highest precipitation. Bormann et al. (1974) speculated that this variability is attributable to individual large storms rather than higher or lower annual totals of precipitation.

Sediment yield from WS 1 in 1978 was more than 3 times that of WS 3 and more than 7 times that of WS 6. In 1980, WS 1 values were twice those of WS 3 and more than 4 times those of WS 6. These values represent natural background variability from watersheds that have not been disturbed since 1920. However, if WS 1 had been cut just prior to 1978, the large sediment yields of 1978 and 1980 would probably have been attributed to logging.

Impacts of Harvesting

It is well known that careless logging practices, particularly the poor design and maintenance of truck roads and skid trails, cause considerable erosion and sedimentation (Patric 1976, 1978). Conversely, it has been hypothesized that forest cutting that does not disturb the forest floor or compact the soil would limit erosion and sedimentation to small amounts from the stream channel (Patric 1978). This hypothesis can be tested using data from WS 2, which was clearfelled with no products removed in 1966 and then treated with herbicides for 3 yr (Table 2).

In the comparison (Table 2) of sediment yields between two undisturbed watersheds and clearfelled WS 2, only the annual values are presented for comparison. This case study approach, as opposed to statistical analyses, was necessary

Table 2. Comparative sediment yields from two undisturbed forested watersheds (WS 1 and WS 6) and WS 2, which was clearfelled in 1965 and sprayed with herbicides in 1966, 1967, and 1968. No wood products were removed, and there were no skid trails or roads on the watershed.

Year	WS-1	WS-2	WS-6
		(kg/ha)	
1966	—	13	4
1967	—	67	31
1968	—	92	10
1969	—	195	13
1970	—	365	42
1971	—	97	5
1972	—	22	6
1973	—	150	95
1974	—	—	25
1975	68	—	18
1976	20	13	15
1977	62	54	79
1978	131	51	18
1979	61	16	25
1980	141	19	32
1981	41	54	34
1982	47	18	10
1983	10	3	3
1984	84	39	35
1985	7	6	4
1986	52	50	17
1987	108	111	52
1988	6	7	1
1989	18	13	7
1990	13	19	13

since there were several years of missing record among the three watersheds being compared.

Particulate matter exported from the first 5 yr of this study was described in detail by Bormann et al. (1974), and we have analyzed additional years of data. Sediment yields from undisturbed WS 6 for 1966 through 1990 ranged from 1 to 95 kg/ha (Table 2). WS 2 exceeded that range only five times: 1969, 1970, 1971, 1973, and 1987. Sediment yields were high in all watersheds in 1973 and 1987 due to the pattern of storm events.

The high sediment yields for 1969 through 1971, and possibly 1973, probably were related to the clearfelling and herbicide application. Streams at Hubbard Brook are characterized by a series of pools and cascades created by coarse woody debris. Since WS 2 had been clearfelled and then sprayed with herbicides for 3 yr, there was no material to replenish these dams. By 1969, the dams had decomposed and washed away. The greater velocities and greater base flows coupled with root system mortality from the herbicide caused the stream banks to fail and the stream to widen and contribute to sedimentation. While these increases in particulate matter seem large when compared with WS 6 (Table 2), they are modest compared with the adjacent, uncut WS 1, which lost as much as 141 kg/ha/yr during the period. On the basis of this comparison, WS 2, despite being clearfelled and sprayed with herbicides, exported more particulates than can be expected from uncut forests only in 1970, the fifth year after clearfelling, and even then by only 2.6-fold.

The treatment of WS 2 was experimental and did not reflect the usual kinds of harvest taking place in New England, and was more severe as a result of herbicide applications for 3 yr in succession. But it demonstrates that erosion can occur on watersheds where no equipment has disturbed the soil, if buffer strips of trees are not left along the streams to provide woody debris and foliage to maintain the debris dams after cutting (Bilby and Likens 1980).

To test a more typical harvest, WS 5 was subjected to a mechanized, whole-tree clearcut in the winter of 1983–1984 All stems greater than 5 cm dbh were felled using a track-mounted, swing-to-tree, feller-buncher. Ninety-six percent of the aboveground biomass was removed by rubber-tired, articulated, cable skidders.

Such mechanized, whole-tree clearcutting can result in severe site disturbance due to increased traffic, and the use of more mechanized equipment (Hornbeck et al. 1986). On WS 5, 70% of the forest floor was disturbed (Table 3), 25% of the watershed was exposed mineral soil after the logging (types scalped, mineral mounds, and mineral ruts), and 33% of the watershed suffered some compaction (types: depressed, organic ruts, and mineral ruts). These levels of soil disturbance are typical of whole-tree clearcuts throughout New England (Martin 1988, Ryan et al. 1992).

In the comparison of undisturbed WS 6 with whole-tree harvested WS 5, a regression approach was used. A linear regression and associated 95% confidence intervals were established between sediment yields from WS 5 and WS 6 for a 9-yr, preharvest, calibration period. In the 8 yr following harvest, increases in annual sediment yield were attributed to

Table 3. Percentages of area disturbed by type of disturbance from 81 transects measured before and after whole-tree clearcutting on WS 5. Transects were 10 m long. The soil surface along each 0.1 m interval was classified into the following types undisturbed, depressed where soil surface was undisturbed but had been depressed by a wheel or falling tree, scarified where mineral and organic soil were mixed, scalped where organic horizons were scraped off the mineral soil, mounds of either mineral or organic soil, wheel ruts lined with either mineral or organic soil, vegetation consisting of slash or stumps, and bare rocks more than 10 cm across. More details may be found in Ryan et al. 1992.

Type	Percent	SE
Undisturbed	30.3	2.8
Depressed	3.8	0.8
Scarified	13.0	1.3
Scalped	0.8	0.8
Organic mounds	12.8	1.6
Mineral mounds	5.6	1.1
Organic ruts	10.6	1.4
Mineral ruts	18.1	2.7
Vegetation	1.8	0.4
Bare rocks	3.2	0.7
Total	100.0	

the harvesting operation if they exceeded the 95% confidence intervals.

Sediment yields (including both organic and inorganic materials) are compared with those from adjacent undisturbed WS 6 in Table 4. Before cutting, sediment yields from WS 5 ranged from 12 to 134 kg/ha. After cutting, sediment yields ranged from 6 to 208 kg/ha. Regression techniques indicated that sediment yields in 1984, the year of the cut, were similar to precutting levels despite receiving 309 mm of precipitation in May. Values for 1985 through 1987 exceeded those that could have been expected if the watershed had not been cut. But the 1985 and 1986 values were less than the highest precutting value of 1977. The 1987 value was twice the predicted value and exceeded the previous maximum by 74 kg/ha.

Stream Turbidity

Stream turbidity resulting from erosion and sedimentation is seldom a problem from undisturbed forests in New England. Turbidity in grab samples of streams draining forests that have not been cutover recently are nearly always less than the drinking water standard of 10 Jackson Turbidity Units (JTU) (Hornbeck et al. 1987).

Forest harvesting need cause only minor increases in stream turbidity during and after logging. This has been demonstrated on WS 4 and 101 at Hubbard Brook. During and after harvest, 325 stream samples were collected for turbidity analysis from both the control watershed and WS 4, the strip cut, and 160 samples were collected from WS 101, the block clearcut (Hornbeck et al. 1987). A summary of these samples by turbidity class is shown in Table 5. About one-half of the samples were collected during storm events and should represent maximum effects of harvest.

Table 4. Sediment yields from WS 5, which was whole-tree clearcut with heavy mechanized equipment in the winter of 1983-1984, and the adjacent WS 6, which has been undisturbed since 1920. The numbers in parentheses were determined from a preharvest regression, and are estimates of sediment loss if the watershed had not been cut. Values with an asterisk exceed the 95% confidence interval about the regression and increases over the predicted value can be attributed to the harvesting operation.

Year	WS-5		WS-6
	(kg/ha)		
	(Before harvest)		
1975	24		18
1976	12		15
1977	134		79
1978	68		18
1979	97		25
1980	89		32
1981	41		34
1982	35		10
1983	14		3
	(After harvest)		
1984	64	(71)	35
1985	112*	(23)	4
1986	129*	(43)	17
1987	208*	(97)	52
1988	6	(18)	1
1989	15	(28)	7
1990	44	(37)	13

Table 5. Number of samples collected for postharvest turbidity analysis.

	Jackson Turbidity Units			
Item	<1	1–5	6–10	11–40
Control				
Nonstorm periods	175	3	0	0
Storm events	143	4	0	0
Total	318	7	0	0
WS 4 (Strip cut)				
Nonstorm periods	171	2	2	3
Storm events	130	9	2	6
Total	301	11	4	9
WS 101 (Block clearcut)				
Nonstorm periods	52	5	1	1
Storm events	88	10	2	1
Total	140	15	3	2

The 11 samples falling in the 11-40 JTU class are probably the result of logging disturbances, especially since there were no corresponding values for the control watershed. More importantly, turbidity values remained low and seldom exceeded 1 JTU.

Carelessness during logging can result in significant increases in turbidity. On a watershed in northern New Hampshire that had been subjected to a whole-tree harvest, stream turbidity during the postharvest period reached a maximum of 3,300 JTU (Hornbeck et al. 1986). This peak value resulted from the failure of a skidroad culvert. Other whole-tree harvests in Maine and Connecticut resulted in more typical maximum turbidities of 17 and 8 JTU, respectively (Hornbeck et al. 1986).

Relationships to Best Management Practices

Silvicultural activities, including logging, were designated potential nonpoint sources of water pollution by the 1972 Clean Water Act and by the 1987 Water Quality Act. To comply with these Acts, all New England states have established Best Management Practices (BMPs) to control erosion and sedimentation from forestlands. Likewise, New England's National Forests have adopted similar or stricter measures in the standards and guides within their Forest Plans.

These BMPs have been published as guides for loggers, foresters, and landowners (Table 6). Both New Hampshire and Vermont have conducted evaluations of their individual state BMPs to determine their effectiveness (DeHart 1982, VT. Agency Environ. Conserv. 1982).

While the watersheds discussed in this paper were cut prior to the publication of the state BMPs, most of the logging techniques required by the BMPs were used effectively to control erosion and sedimentation.

Table 6. State agencies responsible for administering Best Management Practices

State	Agency address and phone	Handbooks available from agency
Maine	Maine For. Serv. Station 22 Augusta, ME 04333 (207) 289-2791	Anonymous. *Erosion and Sediment Control Handbook for Maine Timber Harvesting Operations Best Management Practices*
New Hampshire	Dep. Resour. and Econ. Dev. Div. For. and Lands P.O. Box 856 172 Pembrook Road Concord, NH 03302-0856 (603) 271-3456	Cullen, J.B. *Best Management Practices for Erosion Control on Timber Harvesting Operations in New Hampshire*
Connecticut	Dep. Environ. Prot. Div. For. 165 Capitol Ave., Room 260 Hartford, CT 06106 (203) 566-5348	Anonymous. *Timber Harvesting and Water Quality in Connecticut: A Practical Guide for Protecting Water Quality While Harvesting Forest Products*
Massachusetts	Div. For. and Parks 100 Cambridge Street Boston, MA 02202 (617) 727-8893	Kittredge, D.B., Jr., and M.L. Parker. *Massachusetts Best Management Practices: Timber Harvesting Water Quality Handbook*
Rhode Island	Div. For. Environ. 1037 Hartford Pike North Scituate, RI 02857 (401) 644-3367	Cassidy, G.J., and J.B. Aron. *Best Management Practices*
Vermont	Dep. For., Parks, and Rec. 103 South Main Street 10 South Building Waterbury, VT 05676 (802) 244-8716	Anonymous. *Acceptable Management Practices for Maintaining Water Quality on Logging Jobs in Vermont.* Bihun, Y. *Wetlands Rules and Regulations: What They Mean to Your Logging Operation in Vermont*

Conclusions

Sediment yields from undisturbed northern hardwood forests of New England are among the lowest in North America averaging about 40 kg/ha/yr, but yields as high as 150 kg/ha/yr can be expected. They are not related to watershed size and are not well correlated between watersheds. They are highly variable from year to year and are not particularly related to annual precipitation. They are related to the occurrence of individual large storms.

Increases in sediment yields following logging are usually attributed to the disturbance of the forest soil by equipment. But sediment yields may increase following cutting even where the soil is not disturbed as in winter logging. A buffer strip of trees left to provide woody debris and foliage to maintain debris dams in the stream is essential.

Erosion, sedimentation, and turbidity associated with logging need not be major concerns in New England forests. WS 5 at Hubbard Brook was commercially whole-tree clearcut. Ninety-six percent of the biomass was removed, and 70% of the forest floor was disturbed. Yet, during the year of the logging, sediment yields were the same as before logging. Sediment levels did increase significantly the following 3 yr, but levels were below precutting maximums for 2 of those years, and the third year was a modest increase.

Erosion, sedimentation, and turbidity need not be major concerns in New England forests if BMPs are followed closely. BMPs usually include guidelines for:

1. Steepness of truck roads and skid trails.
2. Water control devices, including the construction and spacing of waterbars and broad-based dips.
3. Culverts, including type, size, spacing, and installation recommendations, such as ditch construction when seeps are involved.
4. Buffer strips of trees along stream channels to provide shade and a source of woody debris.
5. Filter strips of undisturbed land between disturbed sites and streams to trap sediment.
6. Filter devices such as hay bales to prevent sediment from flowing from a road, skid trail, or landing directly into a stream.
7. Minimizing the addition of logging slash and tree tops to streams and removal of this material when necessary.
8. Crossings of streams by roads or skid trails using culverts or bridges.
9. Location of landings, and control of petroleum products and human waste.
10. Closing of logging operations during unfavorable weather
11. Closing and rehabilitation of roads, landings, and skid trails which often involves grooming, seeding, and mulching.

BMPs for individual New England states can be obtained from the offices listed in Table 6.

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