Harvesting

SOIL DISTURBANCE AND PRODUCTIVITY FROM WIDE-TIRED SKIDDER TRIALS IN MINNESOTA ASPEN HARVESTS

Mathew F. Smidt and Charles R. Blinn[1]

Abstract—The soil disturbance and productivity of wide-tired and narrow-tired skidders was compared on aspen harvests in east-central Minnesota. Split plot comparisons showed that wide-tired skidders (73-44.00x32 tires) had cycle times 16 percent greater than the narrow-tired skidder (30.5Lx32 tires) for an average travel distance of 160 meters. The increased total cycle time for the wide-tired skidder came partly from significantly greater load building time. Since adequate traction and flotation were available throughout the harvest trials, wide-tired skidders had no advantage in any of the cycle elements. No significant difference was detected for production (tonnes/productive machine hour) partly due to small sample size. The mineral soil upland sites used in the study did not present any difficulty in operability for either skidder. The area in shallow depressions and ruts ranged from 2 to 23 percent (mean = 12 percent) with no significant difference due to tire size. During the study the application of the wide-tired skidder was affected by 1) poor truck access over haul roads and landings which restricted activity when soils were wet and 2) other production bottlenecks such as trucking limitations and volume quotas which limited operation productivity.

INTRODUCTION

In the Lake States, harvesting operations are often restricted during and following the spring snow melt (often referred to as spring break-up) because of the potential of soil damage and low harvesting productivity. Operators can be idle for as long as three months in this period. In an effort to recover productive time during this period and decrease soil impact throughout the growing season loggers are experimenting with wide tires.

A number of production trials comparing skidders with wide tires to those with conventional tires reported increased skidder productivity for wide-tired skidders on wet, level terrain (Hassan and Gupta 1988, Heidersdorf and Ryans 1986, Mellgren and Heidersdorf 1984, Novak 1988). In addition to productivity benefits, the increased mobility of skidders equipped with wide tires was also an important production benefit (Meek 1994, Mellgren and Heidersdorf 1984, Novak 1988).

Comparison of rutting in operational trials on swampy sites showed that while wide tire application reduced rut depth, the total coverage of ruts was only slightly lower for wide-tired skidders (Groot 1987, Heidersdorf and Ryans 1986, Novak 1988). Although wide-tired skidder use reduced soil compaction and maintained higher infiltration when compared to the narrow-tired skidder use, Aust and others (1991) cautioned that operation of skidders on wet sites made possible by wider tires could produce greater soil impact due to the increased site access not possible with narrow tires.

While the primary motive of wide tire use may be to decrease site disturbance, production comparisons may provide loggers and foresters with decision criteria for wide tire application. The objectives of this research were to compare a) the production of wide-tired and narrow-tired skidders on upland aspen sites and b) the soil disturbance resulting from the trials.

SITE DESCRIPTION

Research sites were established in northern Kanabec and Mille Lacs counties of east-central Minnesota. Each of the five sites were between six and eight hectares in size. The forest cover was generally aspen and mixed hardwood forest that varied slightly in composition, topography, and drainage. Tree volume, volume per acre, and stand basal area varied slightly among the sites (table 1).

The gently sloping sandy loam soils on the research sites were derived from glacial till. The soils were generally classified as having moderate drainage, but the dense till layers about 50 to 100 centimeters below the surface restricted drainage. Each site included small wetland or low areas with organic surface horizons. Site 1 had slightly better drainage than sites 2, 3, and 4. Site 5 had the poorest drainage and approximately 40 percent of the site was covered by poorly drained soils with organic surface horizons. Sites 1 and 4 had the most topographic relief (5-20 percent slope), sites 2 and 3 were gently rolling (5-10 percent slope), and site 5 was nearly flat (0-5 percent slope).

METHODS

The sites were divided into approximately equal halves or harvest areas for application of either the wide-tired or narrow-tired skidder. The harvest of sites 1 and 2 began in mid July and was completed at the end of August in 1991. In 1992 harvesting commenced on site 3 on May 25 and all sites were harvested by July 17. Efforts were made to begin harvesting as early as possible, but the poor condition of site access roads delayed harvesting in both years to the dates listed.

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Table 1—Stand variables for each harvested site

	Site				
Stand variable	1	2	3	4	5
Volume/tree (m^3)[a]	0.20	0.29	0.21	0.30	0.27
Merchantable trees (#/ha)[a]	449	480	380	395	296
Volume/hectare (m^3/ha)[a]	88	138	80	119	80
Basal area (m^2/ha)[b]	24.7	32.5	22.8	31.1	24.4

[a] Northern red oak was excluded. Merchantability standards were dbh > 15 cm, top diameter >10 cm (dob), and merchantable height > 5 m.
[b] Included all trees with dbh > 2.5 cm.

In 1991 the logging firm had two skidder operators, one operator for each skidder-tire combination. In 1992 a single operator was used for both skidders. All operators had extensive experience (> 5 years) in skidder operation and at least one year of experience with the wide-tired skidder.

Trees were skidded to the landing in tree-length form on all sites except site 5 where it was full-tree skidded and chipped at the landing. A John Deere (JD) 640D grapple skidder was employed for most of the study with limited use of a JD 648D grapple skidder (site 1 and 4). The narrow-tired skidder was equipped with 30.5Lx32 tires, and the wide-tired skidder was equipped with 73-44.00x32 tires. The JD 648D was used only as the narrow-tired skidder. In 1991 felling was accomplished with a JD 643 equipped with 64-34.00x26 tires in wide-tired configuration and 28Lx26 tires in the narrow-tired configuration (sites 1 and 2). In 1992 a Case tracked excavator with a feller-buncher head was used for felling all harvests (sites 3, 4 and 5).

Soil Conditions

Forty-four permanent plots were located randomly throughout each site prior to harvest for collection of soil information. On the same day that the area around the plot was skidded, soil samples were collected with a probe from undisturbed soil near the permanent plot markers from 0 to 20 centimeter and 20 to 40 centimeter depths. The soil samples were dried for 24 hours at 105° C and the gravimetric soil moisture was calculated.

The soil disturbance sampling technique was based on that described by Howes and others (1983). The permanent plot markers were used as starting points for the transects. Ten points, 3 meters apart, were located along the transect which was oriented at a random azimuth. The area below each point was categorized as undisturbed, slash covered, rutted, mineral soil exposure, water covered, rocks, or stumps. The points with possible soil compaction were categorized as shallow depressions (< 5 centimeters), moderate ruts (≥ 5 and < 15 centimeters), and deep ruts (≥ 15 centimeters). Mineral soil exposure included conditions ranging from mixed mineral soil and organic matter to complete removal of the surface organic layer.

The proportion of area compacted (shallow depressions and all ruts), moderate and deep ruts combined (≥ 5 centimeters), no disturbance, and all disturbance (all compacted classes plus mineral soil exposure) were the dependent variables modeled with a transformed logistic model (Neter and others 1985). The model included site, treatment (wide-tired or narrow-tired skidder harvest), and the interaction of site and treatment. The surface soil moisture (0 to 20 centimeters) for each sampling point was included as a covariate. The F ratio for the treatment was formed by the ratio of treatment mean square to the interaction mean square appropriate for nested designs.

Continuous Timing and Production

During the narrow- and wide-tired skidder harvests, 50 to 100 entire skidding cycles were timed midway though each harvest. The major skidding elements timed were unloaded travel, loaded travel, load building, delay, piling, and trail building. Load building included all maneuvering and hookup activities to build the load. Location of landmarks and permanent plot locations were used to estimate the loaded travel distance or travel distance(from the landing to the first bunch collected). Travel distance was collected for each cycle regardless of continuous timing. Missing data resulted in different sample size for elements. During continuous timing load size was measured only as trees per load.

The cumulative production data were collected over 2 to 5 days of production from each harvest area. To make up for the small number of sites, additional cumulative production samples were created from each site when the operation stopped completely due to circumstances like serious breakdown or poor weather conditions. A total of 15 production samples were collected. Data collected included total production (stick or weight scaled in tonnes), total productive time, number of cycles, and fuel use, and the travel distance for each cycle. From those data total cycle time, average load size, average travel distance, production per hour, and fuel consumption were calculated.

The dependent variables from continuous timing and cumulative production data were modeled using the GLM procedure (SAS Institute 1988) with the expanded model: site, treatment (tire: narrow or wide), travel distance (covariate), and the interactions tire*site and tire*travel distance. If the F value (type III sums of squares) for the interaction, tire*travel distance, was not significant ($P < 0.10$), it was deleted from the model and a reduced model was used.

RESULTS AND DISCUSSION

Soil Disturbance

Soil moisture conditions on sites 1, 3, 4, and the narrow-tired area of 5 had similar average soil moisture at both soil depths (table 2). Organic areas within the wide-tired area of site 5 had increased average soil moisture, and the August harvest date of site 2 resulted in considerably drier soil during the harvest.

Tire size was not a significant factor in any of the disturbance measures ($P < 0.10$), and site was largely the only significant term in the models. Even with moist soil conditions throughout the sites, soils provided generally adequate support for the equipment as indicated by the low coverage of deep ruts across all sites (table 3). The low level of soil disturbance on site 2 could be related to the dry soil. The low soil disturbance on site 5 was produced in part by the concentrated skidding pattern present. Relatively high levels of disturbance, especially on sites 1 and 4, resulted from the high skid trail density produced by unplanned skid trails. The change from wheeled (sites 1 and 2) to tracked feller buncher (sites 3, 4, and 5) was not obvious from the site totals, but was correlated with generally drier (sites 1 and 2) and generally (sites 3, 4, and 5) wetter soil conditions in the successive harvest years.

Continuous Timing and Production

Model P values were generally lower for the cumulative production data than for continuous timing data due in part to the smaller sample size and the increased error

Table 2—Completion date and average soil moisture data for the harvest areas harvested by the wide-tired (W) or narrow-tired (N) skidder

Site	Harvest date	Harvest area	Gravimetric soil moisture	
			0 to 20 cm	*20 to 40 cm*
1	7/91	W	0.38	0.22
		N	0.38	0.22
2	8/91	W	0.18	0.12
		N	0.20	0.14
3	6/92	W	0.39	0.26
		N	0.33	0.19
4	6/92	W	0.39	0.26
		N	0.39	0.24
5	7/92	W	0.69	0.36
		N	0.36	0.25

Table 3—Soil disturbance categories for the narrow-tired (N) and wide-tired (W) skidder harvest areas for each site. Totals do not equal 100 percent since coverage of natural water filled depressions, stumps, and rocks was omitted

	Site									
	1		2		3		4		5	
Disturbance class	W	N	W	N	W	N	W	N	W	N
1) Shallow depressions (<5 cm)	18	10	5	7	8	8	14	12	7	2
2) Moderate ruts (> 5 cm,< 15 cm)	5	2	2	1	2	5	3	6	0	0
3) Deep ruts (> 15 cm)	0	1	1	0	1	1	1	1	0	0
Total depressions (TD)(1 + 2 + 3)	23	13	8	8	11	14	18	19	7	2
Slash cover	17	20	20	20	14	17	15	22	15	21
Mineral soil (MS)	27	40	33	41	36	38	36	30	25	29
Total disturbed (MS + TD)	50	53	41	49	47	52	54	49	32	31
Total undisturbed	18	26	37	27	36	26	30	30	49	43

explained by the covariate, travel distance, in the continuous timing models (table 4). In the continuous timing data each cycle had a travel distance estimate whereas in cumulative production data the total cycle time and travel distance where averages for that cell. In the continuous timing models, significant ($P < 0.10$) differences for tire size were found for load building time and for travel distance and tire interactions for total cycle time and delay. In the cumulative production data a significant difference was found for only total cycle time.

With the continuous timing data the difference between wide-tired and narrow-tired skidder total cycle time increased with increasing travel distance. This was indicated by the significant interaction, tire*travel distance. The total cycle time for the wide-tired skidder increased with travel distance about 22 percent faster than the narrow-tired skidder total cycle time (figure 1). The delay model also had a significant interaction, tire*travel distance, and produced results similar to the total cycle time model with respect to the wide-tired skidder. Although the delay model is significant, the R^2 is only 0.055 compared to over 0.30 for all other element models. The interaction term was not significant for any other element, but the model predicted load building times 0.38 minutes/cycle greater for the wide-tired skidder across all travel distances.

In trials on wet terrain the cycle time advantage for wide-tires was produced during the travel elements of the cycle (Hassan and Gupta 1988, Heidersdorf and Ryans 1986, Mellgren and Heidersdorf 1984, Novak 1988). The similarity of unloaded and loaded travel times in this trial might indicate that the wide-tires were not able to produce improvements in traction or reduction in slip because of the relatively firm soil conditions present throughout the harvests. Similar or smaller increases in load building time for wide-tired skidders over narrow-tired skidders have been reported in the previous trials. The delay time difference is difficult to explain since reasons for the delays in this study were not completely specified. The significant differences might result partially from confounding among site, delay time, and travel distance. Travel distance and site are somewhat confounded since a few sites contribute the majority of very long travel distances. The confounding problem is greater with the continuous timing data since most of the data for a site is taken over the more limited range of travel distances traversed in one or two days.

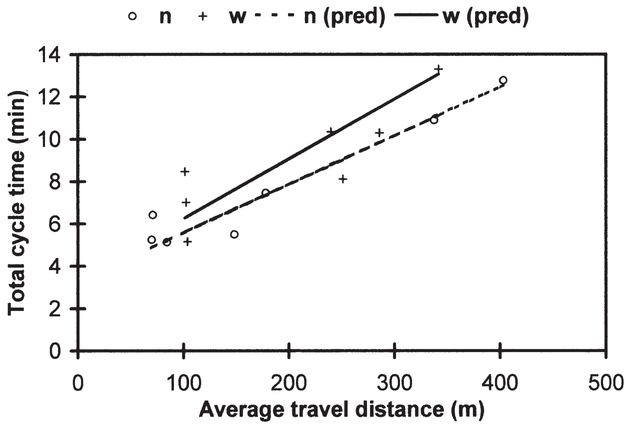

Figure 1—Average observed total cycle time from the harvest areas and predicted total cycle time from the continuous timing model for wide-tired (+) and narrow-tired (o) skidders versus average travel distance.

The high R^2 in the cumulative production models were mainly the result of limited replication within the harvest areas on each site. Only one model, total cycle time was significant at even a high P value of 0.10. The estimate of total cycle time was calculated as the total productive time divided by the number of cycles in the sample period (figure 2). These estimates were larger for a given travel

Table 4—Model R^2, N, and P value and tire, travel distance (TD), and tire*travel distance interaction P values for continuous timing and cumulative production data. If the tire*travel distance interaction was not significant ($P < 0.10$), model, tire, and travel distance interaction P values are from the reduced model without that interaction term

	Model			P values				Model			P values		
Continuous timing	P value	N	R^2	Tire	TD	Tire*TD	Cumulative production	P value	N	R^2	Tire	TD	Tire*TD
Unloaded travel	0.0001	737	0.85	0.422	0.0001	0.549	Total cycle time	0.006	15	0.96	0.093	0.003	0.737
Load building	0.0001	760	0.30	0.020	0.0001	0.631	Production	0.246	15	0.79	0.128	0.191	0.359
Loaded travel	0.0001	776	0.85	0.565	0.0001	0.400	Load size	0.448	15	0.70	0.693	0.365	0.388
Delay	0.0001	894	0.06	0.186	0.0001	0.001	Fuel use (l/t)	0.310	13	0.87	0.359	0.065	0.812
Total cycle time	0.0001	703	0.50	0.370	0.0001	0.001	Fuel use (l/pmh)	0.626	13	0.74	0.271	0.412	0.506

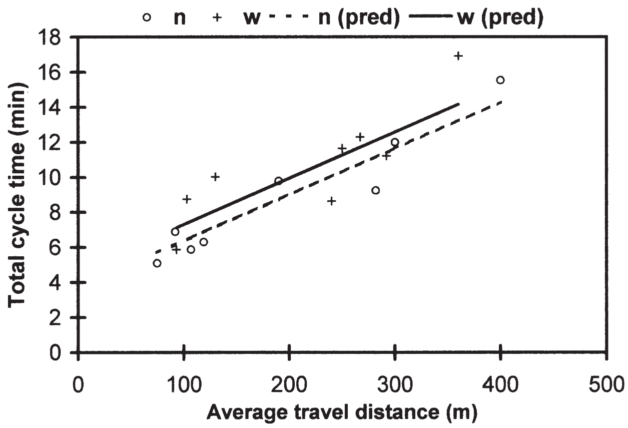

Figure 2—Predicted total cycle time from the cumulative production model and observed sample average total cycle time for wide-tired (+) and narrow-tired (o) skidders versus average travel distance.

distance than those from the continuous timing data, probably because cumulative production data contained the slower production periods that occurred at the beginning and end of the harvests. Total cycle time estimates for the wide-tired skidder were 0.92 minutes/cycle greater than those for the narrow-tired skidder across all travel distances. Significant total cycle time differences did not translate into significant differences in production (figure 3). Variation in load size could have introduced enough variability into production to mask the significant difference observed in total cycle time.

CONCLUSIONS

The relatively dry to moist soil conditions present throughout the study period prevented, for the most part, the demonstration of the advantages of wide-tires evident when used on softer, moister soil. However, wide tires did not produce any significant disadvantage in the travel elements of the cycle. The increased total cycle time for the wide-tired skidder seemed to be the result of accumulated insignificant differences in unloaded and loaded travel time and the significant differences in delay and load building times.

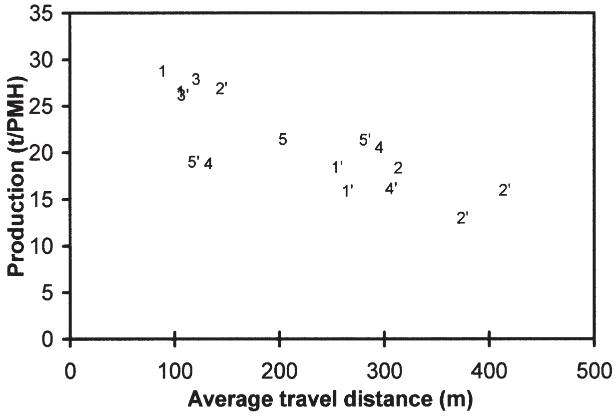

Figure 3—Production estimates versus average travel distance. Observations from narrow-tired harvest areas are indicated by the site numbers (1 - 5) alone. Observations from wide-tired harvest areas are indicated by the site number followed by an apostrophe. 1 and 1' represent narrow-tired and wide-tired skidder observations, respectively, from site 1.

Operators commented that it was more difficult to maneuver around stumps and rocks in the harvest areas due simply to the extra width of the tires. They were operating the wider tires with inflation pressures near 210 kPa due to dealer recommendations to prevent the bead separation from the rim. With the high pressure in the wide tires, jolts from running over obstacles were transferred to the operator rather than at least partially absorbed by the tire. The rougher ride may have been less important in travel element than load building since a relatively obstacle-free path could be chosen for repeated use.

Production bottlenecks might have had considerable effect on both production and total cycle time. Although landing placement emphasized access to all weather roads, the inability of trucks to get to the landing and remove stored wood inhibited production for as many as several days following rains that occurred throughout the study period. Since landing space was constantly limited due to either restricted road access or the supply of trucks, operators had no incentive or ability to increase production. As an example site 5 had similar production across a wide range in travel distance caused by the limited chipper capacity and inadequate supply of chip vans (figure 3).

Differences in site disturbance were also muted somewhat by the firm soil conditions during operation. The near absence of deep rutting indicated the soil's ability to provide both flotation and thrust for both machines. However, the lack of significant difference in areal extent of rutting is a result similar to other studies on much softer and moister terrain. The majority of differences in the areal extent of disturbance and rutting among sites was probably due more to uncontrolled factors such as feller-buncher type and activity, topography, and harvest layout.

The results of this study did not help to significantly clarify issues of comparative productivity of wide-tired and narrow-tired skidders on upland soils similar to these. Unless wet season road and landing access is addressed in harvest planning of upland sites, the operations may be restricted even when the wide-tired machines can provide a production advantage over conventional machines.

Inability to provide access or the lack of production advantages on upland sites would leave the cost of wide tires to be recouped mostly through decreases in site disturbance. The shallow aspen roots which provide the sucker regeneration are severely damaged even by the shallowest ruts (Bates and others 1992, Smidt 1996). Differences in areal extent of disturbance which are controlled mostly by planning on dry and moist upland sites are more critical than disturbance severity.

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IMPACTS OF HARVEST INTENSITY AND SOIL DISTURBANCE ON EARLY TREE GROWTH AND EARTHWORM POPULATIONS IN A MISSOURI OZARK FOREST

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Abstract—The long-term impact of increased removal of forest biomass and nutrients with increased harvest intensity on soil productivity is a general concern. In 1994, a long-term study was initiated in the Missouri Ozarks as part of the National Long-Term Soil Productivity (LTSP) study to study the effects of biomass removal and compaction on soil productivity. The study has three levels each of organic matter removal (boles only, whole tree, and whole tree plus forest floor) and soil compaction (none, moderate, and severe). This report presents 3-year preliminary results from the low and high organic matter removal and soil compaction treatments with and without weed control on survival and growth of planted northern red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and shortleaf pine (*Pinus echinata* Mill.) seedlings. Differences in seedling survival were affected by organic matter removal and soil compaction treatments. Trees with weed control were larger in diameter, taller, and had more diameter and height growth than trees without weed control. Organic matter removal and soil compaction treatments significantly affected the height and diameter growth of trees differently. Analysis of spring and fall samplings of earthworm populations showed that soil compaction and time of sampling significantly influenced the number and biomass of earthworms.

INTRODUCTION

Forest harvesting obviously removes nutrients from the ecosystem. Conventional harvesting removes about 5 to 30 percent of the total nutrients in the aboveground stand, but the average for most forests rarely exceeds 10 percent (McColl and Grigal 1979). Intensive harvesting, which removes a greater proportion of the forest biomass than has traditionally been removed in sawtimber harvests, is contemplated as a means to provide more biomass for fiber, fuel, and chemicals. There is worldwide concern, however, that increased removal of biomass and the associated nutrients may cause a decline in forest productivity. Also, the use of heavy equipment may adversely affect physical properties of the soil causing compaction, loss of porosity, and erosion.

These concerns led to the development of a joint National Forest System/Forest Service Research study (Powers and others 1989) on long-term site productivity (LTSP). The national study has two major objectives. The first is to determine how changes in soil porosity and organic matter affect fundamental soil processes controlling forest productivity and sustainability. The second objective is to compare results from similar replicated studies among major forest types and soil groups across the United States and Canada. This report presents some early results in the Missouri LTSP study of effects of organic matter removal, soil compaction and weed control on the survival and growth of planted trees and earthworm numbers and their biomass.

METHODS AND MATERIALS

Study Site

The oak-hickory (*Quercus* L. - *Carya* Nutt.) forest type is the major timber type in the Central Hardwood Region occurring over a variety of soils, relief, and stand conditions. The Missouri LTSP study is located at the Carr Creek State Forest in Shannon County. Shannon County is located in the southeastern Missouri Ozarks. Mean annual precipitation in the area is 112 cm and mean annual temperature is 13.3°C. The study site is located on the upper northeastern-facing side slopes of two parallel ridges. Both convex and concave landforms occur on the sloping (20 to 28 percent slopes) topography. The weathering of the Ordovician and Cambrian dolomite has resulted in a deep mantle of cherty residuum (Gott 1975). Soils derived from this residuum are primarily of the Clarksville series (loamy-skeletal, mixed, mesic, Typic Paleudults). Prior to harvest, the site had a well-stocked, mature, second-growth oak-hickory forest. The site index for 50 year-old black oak (*Quercus velutina* Lam.) ranged from 74 to 80 feet (Hahn 1991).

Experimental Design

The LTSP study includes nine treatments derived from combinations of three levels each of organic matter removal and soil compaction. The three levels of organic matter removal included (1) merchantable boles removed (boles only, **BO**), (2) All living vegetation removed (whole tree, **WT**), and (3) all living vegetation plus forest floor removed, exposing mineral soil (whole tree + forest floor, **WTFF**). Merchantable boles included trees with diameters at breast height (dbh) of 25 cm or larger. The three levels of compaction included (1) no compaction (**C_0**),

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(2) moderate compaction (**C_1**), and (3) severe compaction (**C_2**). The targeted bulk density of severe compaction treatment was an increase of 30 percent more than the bulk density of the no compaction treatment. The moderate soil compaction treatment was intermediate between the severe compaction and no compaction treatments. Each of the nine treatment combinations was replicated three times. Physical and chemical plot variables were also measured in three uncut (unharvested) plots adjacent to treatment plots in the study. For this report, two levels of organic matter removal and two levels of soil compaction, each with and without weed control, were used (Table 1).

Pre-Harvest Measurements, Site Preparation, Treatment Application, and Sampling

After determining that the key soil properties did not vary significantly across the areas, preliminary plot boundaries were established. Contiguous plots, approximately 0.4 hectare (1 acre) in size, were assigned treatments randomly in the summer of 1993. Five-meter-wide buffer strips were included around all plots. A clearcut area with all vegetation removed, whose width approximated or exceeded the height of bordering trees, separated all treatment plots from residual forest. The pre-harvest inventory of the overstory, understory, herbaceous layer and dead and downed woody material was completed in the summer of 1993 by the Missouri Forest Ecosystem Project forester and botany crew of the Missouri Department of Conservation (Ponder and Mikkelson 1995). Other collections before the harvest were biomass samples from overstory canopy trees, understory saplings, ground vegetation, and leaf litter/humus layer. In addition to 2.5 meter deep soil pits being dug and soil profiles described, soil samples were collected for nutrient and bulk density analyses (Ponder and Mikkelson 1995).

Trees were harvested from February thru May 1994. On plots designated as no compaction, all trees with a dbh of 25 centimeters or larger (merchantable trees) on BO, WT, and WTFF plots were directionally felled and removed with a skyline cable logging system. Merchantable trees on plots where the soil was to be compacted, plot borders, and the area within the study boundary were directionally felled and removed with a skidder that traveled only on designated paths within the plots and in plot borders. After the removal of merchantable trees in BO plots, the remaining trees were felled. This standing biomass included trees with dbh less than 25 centimeters (unmerchantable trees), crowns from merchantable trees, standing dead and live snags, and trees in the herbaceous layer with basal diameters greater than 2 centimeters or at least 25 centimeters tall. Trees were cut into lengths that permitted material to be hand carried, lay on or near the ground, and form a layer of uniform height over the plot. Except for crowns, which were retained on the BO plots but not on WT plots, the remaining biomass on WT plots was treated the same as biomass on BO plots. On WTFF harvested plots, all biomass remaining after harvest was removed. This included all understory vegetation plus the forest floor was raked away to the mineral soil. For BO and WT plots requiring compaction, it was necessary to remove and replace these materials (except the leaf/litter layer) after compaction was completed. Skidders and tractors were permitted on compacted plots, but not on plots that were not to be compacted. A 14-ton vibrating sheep-foot roller was used to compact soil. The roller made passes over the severe compaction treatment until there was no change in bulk density after roller passes. For bulk density measurements, soil cores (30 centimeters in length x 9.2 centimeters in diameter) were extracted from each plot using a soil-coring device (Ponder and Alley 1997). The cores were divided into 10-centimeter depth increments, oven dried at 105°C, and weighed. Bulk density for each sample was calculated according to the method of the Soil Survey Staff (1984). Soil bulk density measurements were taken after the roller made one, three, five, and eight passes over plots that received the severe compaction treatment. Changes in bulk density usually ceased after five passes.

Table 1—Treatment combinations for two levels each of organic matter, compaction, and weed control in a Missouri forest

Treatment	Organic matter removal	Soil compaction	Weed[a] control
BOC_0	BO	C_0	With
BOC_0	BO	C_0	Without
BOC_2	BO	C_2	With
BOC_2	BO	C_2	Without
$WTFFC_0$	WTFF	C_0	With
$WTFFC_0$	WTFF	C_0	Without
$WTFFC_2$	WTFF	C_2	With
$WTFFC_2$	WTFF	C_2	Without

[a] Each treatment plot split on weed control treatment.

In late spring of 1994, all plots were planted with 1-0 red oak, white oak, and shortleaf pine in a 3:3:1 ratio, (3 red oak seedling plus 3 white oak seedlings to 1 shortleaf pine seedling), using hoedads. Seedlings were planted in rows at a spacing of 2.5 meters by 2.5 meters. A 3-foot radius area around each seedling was sprayed with a glyphosate and simazine mixture to control weeds. Beginning in the 3rd growing season (1996), half of each plot was kept weed-free to permit planted trees to grow freely. The other half of the plot was allowed to develop naturally. Net primary productivity in these two plant communities will provide direct measures of productivity as influenced by study treatments.

Seedling heights and diameters at 2.5 centimeters above the ground were measured immediately after planting, and annually thereafter. Twelve 900-centimeters^2 subplots of herbaceous or ground flora samples were collected from each plot annually in the fall for dry weight and nutrient element concentration. Samples were clipped, placed in paper bags, air-dried before oven drying, weighed, ground in a Wiley mill and sent to the Ohio Research Analytical Laboratory for elemental analyses.

Earthworm Sampling

Plots were sampled for earthworms in the spring and fall of 1995, the second year after completing the installation of the study. Ten earthworm-sampling units were taken randomly at approximately the same distance apart across each plot: 5 from the upper 1/3 of the plot (top) and 5 from lower 1/3 of the plot (bottom). Each sampling unit measured 30.5 centimeters (length) x 30.5 centimeters (width) x 15 centimeters (depth). Earthworms were also collected from three uncut plots. Earthworms in top and bottom samples were combined for statistical analysis.

Earthworms were hand-sorted, counted, and placed in specimen cups containing about one-third volume of soil and stored in ice chest immediately. Earthworms were later recounted and preserved in formalin before being identified using the internal characteristic identification method of James (1990). Earthworms were dried in an oven at 60°C for 48 hours and dry weights were recorded. The oven-dried earthworms were ashed in a muffle furnace at 500°C for 4 hours and the ash weights recorded. Earthworm biomass was calculated by subtracting the ash weight from the dry weight (Parmelee and others 1990).

Statistical Analyses

The experiment was analyzed as a split-plot design with three replications, with organic matter removal and compaction treatments as the main plots and the weed control treatments as the subplots. Analysis of variance procedures were conducted with the PROC GLM procedures in SAS (SAS Institute, 1987). Survival data were analyzed using SAS (Allison 1995). Prior to analysis, the data were transformed to equalize variance using log10 transformation. Data were analyzed using analysis of variance and comparisons were made using the Least Significance Difference (LSD) test. Unless otherwise noted, all statistical tests were performed at the (α = 0.05 level of significance.

RESULTS AND DISCUSSION

Bulk Density

The severe soil compaction treatment effectively increased the bulk density over the no compaction treatment (Table 2). Bulk density generally increased with depth. The percent change in bulk density between the no compaction treatment (0 passes) and the severe compaction treatment (5 or more passes) was 22, 29, and 26 percent for the 10, 20 and 30 centimeter depth increments, respectively. Although soil compaction levels for the severe soil compaction treatment were not at the targeted level of 30 percent greater than the levels for the no soil compaction treatment, the differences were significant at the 0.05 level.

Table 2—Mean soil bulk density measurements for no compaction and severe compaction treatments. Soil compaction was done with a 14-ton vibrating sheep-foot roller

	Bulk density	
Depth	No compaction	Severe compaction[a]
Cm	------------------ *G/cm³*	------------------
0 - 10	1.26(±0.2)[b]	1.61(±0.09)
11 - 20	1.33(±0.23)	1.88(±0.08)
21 - 30	1.56(±0.27)	2.12(±0.37)

[a] Five or more passes.

[b] Numbers in parenthesis are standard deviation of mean based on 12 samples.

Survival

After three years, weed control had no significant effect on survival of the planted seedlings (Table 3). However, there were survival differences associated with organic matter removal and soil compaction for each species. Survival for all species was significantly lower in the BO treatments compared to the WTFF treatments. Also, survival was better for all species in the severe soil compaction treatment than in the no compaction treatment. Most of the mortality occurred during the first year (1994) after planting (Table 4). Some of the mortality was undoubtedly caused by the late planting period of May thru June.

Table 3—Survival of planted northern red oak, white oak, and shortleaf pine with two levels each of organic matter removal (removal), compaction, and weed control three years after site preparation and treatment application in the Missouri LTSP study

Treatment	Red oak	White oak	Shortleaf pine
	------------------	*Percent*	------------------
Removal[a]			
BO	76.1a[b]	77.3a	64.0a
WTFF	90.5b	87.4b	68.5b
Compaction			
C_0	79.4a	79.3a	60.4a
C_2	87.0b	85.8b	70.3b
Weed control			
With	80.2a	80.3a	60.1a
Without	78.2a	73.3a	57.6a

[a]BO means boles only and WTFF, whole tree plus forest floor removal.

[b]Values in a column for a tree species and for a parameter are not significantly different (α=0.05) when followed by the same letters.

Table 4—Survival of planted northern red oak, white oak, and shortleaf pine after one two and three years following site preparation and treatment application in a harvested Missouri forest stand

	With weed control			Without weed control		
Treatment[a]	1995	1996	1997	1995[b]	1996	1997
	Percent					
Northern red oak						
BOC_0	77	72	68a[c]	69	66	62a
BOC_2	95	93	84b	89	86	77b
$WTFFC_0$	97	96	91b	97	97	93b
$WTFFC_2$	94	93	90b	94	94	92b
White oak						
BOC_0	78	73	72a	72	71	63a
BOC_2	86	86	82ab	80	80	79a
$WTFFC_0$	93	93	86b	95	95	78a
$WTFFC_2$	96	95	88b	93	93	84b
Shortleaf pine						
BOC_0	47	47	46a	50	47	46a
BOC_2	82	82	82b	90	90	90b
$WTFFC_0$	78	78	75b	63	60	50a
$WTFFC_2$	58	58	58a	71	71	70ab

[a] BO means boles only and WTFF, whole tree plus forest floor removal.
[b] All trees had weed control in 1995.
[c] Values in a column for a tree species are not significantly different (α=0.05) when followed by the same letters.

The lack of survival differences between weed control treatments is not a surprise. All plots received weed control treatments for the first two years after planting. Without weed control during the first several years after planting, seedlings planted in harvested stands using conventional procedures usually have very poor survival. Much better survival has been known to occur when large diameter seedlings are planted beneath shelterwood systems (Johnson and others 1986). It appears that part of the reason for the relative low survival of trees in BOC_0 treatment where only boles were removed and there was no soil compaction treatment may be due to the somewhat better growth of invading herbaceous vegetation. Although the weight of herbaceous vegetation did not differ significantly between treatments, they ranked in the order of BOC_0 > $WTFFC_0$ > BOC_2 > $WTFFC_2$. Also, the uncompacted plots tended to have more surviving natural trees and sprouts. Many existing small trees and shrubs were killed or severely damaged during the soil compacting process. Also, damaged stumps in the severe compaction treatment produced few sprouts. Removing the forest floor also eliminated seeds from the plots and exposed others that might have been eaten by birds and rodents.

Growth

Both diameter and total diameter growth of trees three years after planting were significantly affected by treatments (Table 5). Treatments affected species differently. Organic matter removal affected both the diameter and the total diameter growth of both red and white oak, but not shortleaf pine. Diameter growth was more than two times and nearly two times greater for red oak and white oak, respectively, in the Bo treatment compared to the WTFF treatment. Neither was diameter or total diameter growth of any of the trees tested significantly affected by compaction treatments, but weed control did. Trees with weed control were larger in diameter and had more diameter growth than trees without weed control. There were significant interactions between organic matter removal and weed control, and organic matter removal and compaction for diameter, and between organic matter removal and weed control for total diameter growth for white oak. Both diameter and total diameter growth followed the order of BO with weed control > WTFF with weed control > BO without weed control > WTFF without weed control. The diameters of white oak trees for the significant interaction between organic matter removal and compaction were BOC_2 > BOC_0 > $WTFFC_2$ > $WTFFC_0$.

Except for shortleaf pine, trees with weed control were significantly taller than trees without weed control (Table 6). Total height growth of northern red oak was also significantly better with weed control than without it. Organic matter removal did not affect total height growth of of any of the species tested, but it did significantly affect the height of white oak. White oak in the BO treatment was taller than

Table 5—Diameter and total diameter growth of planted northern red oak, white oak, and shortleaf pine with two levels each of organic matter removal (removal), compaction, and weed control three years after site preparation and treatment application in the Missouri LTSP study

	Diameter			Total diameter growth		
Treatment	Red oak	White oak	Shortleaf pine	Red oak	White oak	Shortleaf pine
	mm					
Removal[a]						
BO	19.8a[b]	11.5a	22.8a	15.2a	7.0a	20.0a
WTFF	11.4b	8.5b	20.5a	6.7b	3.8b	17.7a
Compaction						
C_0	17.8a	10.3a	20.6a	13.2a	5.9a	17.9a
C_2	11.7a	9.7a	20.6a	6.9a	5.0a	17.7a
Weed control						
With	21.2a	11.5a	25.3a	16.6a	7.1a	22.6a
Without	9.5b	8.3b	17.9b	4.8b	3.8b	15.1b

[a] BO means boles only and WTFF, whole tree plus forest floor removal.

[b] Values in a column for a tree species and for a parameter are not significantly different (α=0.05) when followed by the same letters.

Table 6—Height and total height growth of planted northern red oak, white oak, and shortleaf pine with two levels each of organic matter removal (removal), compaction, weed control three years after site preparation and treatment application in the Missouri LTSP study

	Height			Total height growth		
Treatment	Red oak	White oak	Shortleaf pine	Red oak	White oak	Shortleaf pine
	Cm					
Removal[a]						
BO	76.9a[b]	57.6a	105.5a	41.7a	41.0a	90.0a
WTFF	73.8a	51.3b	106.3a	40.9a	35.0a	92.0a
Compaction						
C_0	77.2a	54.5a	98.5a	43.3a	38.2a	83.2a
C_2	72.2b	54.1a	115.7b	37.6a	37.4a	101.3a
Weed control						
With	83.7a	60.5a	106.8a	49.5a	43.8a	92.0a
Without	66.6b	47.8b	105.0a	32.5b	31.5a	89.9a

[a] BO means boles only and WTFF, whole tree plus forest floor removal.

[b] Values in a column for a tree species and for a parameter are not significantly different (α=0.05) when followed by the same letters.

white oak in the WTFF treatment. Soil compaction affected the height of northern red oak and shortleaf pine differently. Northern red oaks in the no soil compaction treatment were taller than red oak in plots that were in the severe soil compaction treatment, but the opposite was true for shortleaf pine. There was a significant interaction between soil compaction and organic matter removal for both height and total height growth for white oak. Treatments for height followed the order $BOC_0 > WTFFC_2 > BOC_2 > WTFFC_0$. The order of treatments for total diameter growth followed the order $BOC_2 > BOC_0 > WTFFC_2 > WTFFC_0$.

Earthworms

Soil compaction significantly affected the number of earthworms in both spring and fall samples, but it affected their biomass only in the fall samples (Figures 1 and 2). The number of earthworms found in the spring was 50, 42, and 15 per meter^2, respectively, for uncut, no compaction, and severe compaction treatments. The number of earthworms was considerably higher in soils sampled in the fall than in soils sampled in the spring. They were 132, 89, and 48 per meter^2, respectively, for no compaction, uncut, and severe compaction treatments. Earthworm biomass for fall samples was 5.1, 3.0 and 2.1 grams/meter^2, respectively, for no compaction, uncut, and severe compaction plots. Neither the number of earthworms nor their biomass was significantly affected by organic matter removal treatments in spring or fall samples.

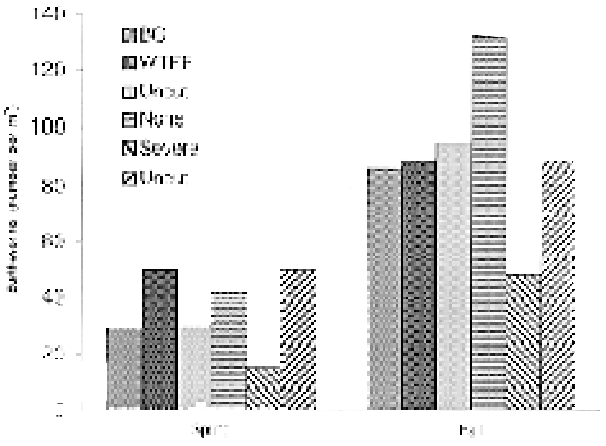

Figure 1—Response of earthworms to organic matter removal (BO, WTFF, and Uncut) and soil compaction (None, Severe, and Uncut) in a Missouri forest.

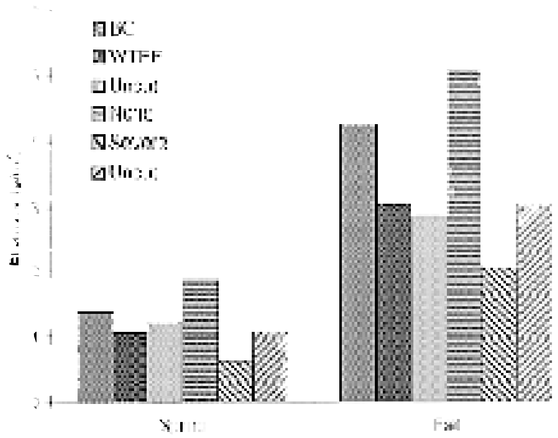

Figure 2—Earthworm biomass affected by organic matter removal (BO, WTFF, and Uncut) and soil compaction (None, Severe, and Uncut) in a Missouri forest.

These observations suggest that soil compaction has, perhaps, been more influential than organic matter removal on tree growth and earthworm activity. Nutrient analyses of the herbaceous vegetation collected in year three of the study showed that except for P, differences between treatments were not significant. The leaf P concentration for herbaceous vegetation from the BOC_0 treatment was significantly higher than the P concentration in herbaceous vegetation from the $WTFFC_0$ and the $WTFFC_2$ treatments. Phosphorus concentration for all four treatments were in the order of $BOC_0 > BOC_2 > WTFFC_2 > WTFFC_0$. Herbaceous samples collected in year two showed N to be significantly different between the BOC_0 treatment and other treatments (Ponder 1997). But the difference was not present in year three. Apparently, nutrient differences caused by biomass removal treatments (Ponder and Mikkelson 1995), which may eventually affect soil nutrient supply, are not currently different enough to be detected consistently in herbaceous samples.

The increase in soil bulk density associated with soil compaction can, depending on the soil moisture content affect the soil strength. Soil strength affects the ability of roots, and perhaps earthworms, to penetrate or move through the soil. Soil compaction also reduces soil porosity. Decreased soil porosity can reduce soil water, cause poor aeration, and affect the distribution and growth of earthworms (Edwards and Bohlen 1966). We do not report soil strength or soil porosity measurements for this study. However, researchers investigating other LTSP sites have reported that after five years, soil strength in compacted plots was significantly higher and soil porosity was significantly lower than for soil in no compaction plots, (Powers and Fiddler 1997; Stone and Elioff 1998).

Because of the cherty, well-drained, soils in the study area, we had expected earthworm numbers to be higher in the spring when soil moisture was believed to be greater. The larger number of earthworms in the fall compared to the spring may be due to, in addition to the effects of soil compaction, the results of a number of soil environmental factors acting alone or interacting with each other. These may include soil temperature, soil moisture, organic matter, and perhaps, the species reproduction patterns.

SUMMARY

Early tree survival was significantly higher in $WTFFC_2$ treatments. Both organic matter removal and soil compaction treatments affected diameter, diameter growth, height, and height growth of tree species differently. Tree growth was also significantly better with weed control than without weed control.

These results are preliminary. The earthworm study along with some more recently initiated monitoring of soil and leaf nutrient analyses, soil moisture, and soil temperature is continuing. Also of interest, will be the long-term effects of weed control on tree biomass production, soil moisture, and soil temperature, and interactions of weed control with organic matter removal and compaction to influence vegetation growth (Powers and Fiddler 1997). Analyses of these data should help to better define the below-ground effects of organic matter removal and soil compaction on tree growth and how earthworms respond to these disturbances. Survival and growth differences among treatments should become more pronounced as the stand continues to develop.

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CONTRASTING TIMBER HARVESTING OPERATIONS ILLUSTRATE THE VALUE OF BMPS

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Abstract—Our paper compares water yield, water quality, and sedimentation from a harvesting operation conducted in 1957 without BMPs to a harvesting operation in 1986 utilizing BMPs. The comparison illustrates the values of BMPs for protecting soils and streams and provides insight into causes of water quality degradation. Both logging operations were conducted on or near the Fernow Experimental Forest located in north central West Virginia. The 1957 logging operation was conducted on a 74-acre watershed using a crawler tractor equipped with an arch. Roads were unplanned "logger's choice" with no limits on grade or location. West Virginia's BMPs were used on a second 96-acre watershed logged with wheeled skidders in 1986. Results indicated that careless logging greatly accelerated sediment yields but development of erosion pavements and natural vegetation quickly reduced them, even with no post-logging care. Although the percentage of area occupied with dozed roads was actually greater (10.6 versus 3.6 percent) on the area logged in 1986 with wheeled skidders, water quality impacts were much less. Average stream turbidity during logging in the absence of BMPs was 490 ppm versus <10 when using BMPs. Sediment loss during active logging was estimated at 2,880 lb/ac on the carelessly logged watershed compared to 110 lb/ac when BMPs were used.

INTRODUCTION

Bare soil exposed during timber harvesting can be a major source of water degradation, but guidelines developed over the years reduce adverse impacts on soil and water resources (Weitzman 1952; Haussman 1960; Kochenderfer 1970; and Pierce and others 1992). Passage of the Federal Water Pollution Control Act Amendments of 1972 required use of BMPs to control nonpoint-source water pollution from forestry activities. Despite application of past research and BMPs, and the goals of present-day forest managers to sustain and protect site productivity, critics of current timber harvesting operations sometimes equate them with less careful logging operations of the past. Thus it is important to demonstrate the improvements of current logging and BMPs in terms of protecting soil and water resources. This paper does so by comparing magnitude and longevity of impacts from a harvesting operation conducted in 1957 without BMPs to a 1986 harvest utilizing them.

STUDY AREAS

Three gaged watersheds located in the unglaciated Allegheny Plateau region of north-central West Virginia were used in this study. Two of them, watershed 1 (WS1) and watershed 4 (WS4), are located on the Fernow Experimental Forest while the Haddix watershed is 4.0 miles away. WS1 and Haddix were logged while WS4 has been retained as a reference watershed to evaluate treatment effects. Precipitation is distributed evenly across the year on all three watersheds; the annual average is 58 inches on the Fernow and 54 inches on Haddix. Annual runoff from WS4 during the study periods averaged 26 inches, 6 inches during the growing season and 20 inches during the dormant season. Other pertinent characteristics are shown in Table 1.

WS1 supports a 40-year-old stand of mesic hardwoods that originated after cutting in 1957-58, plus some scattered cull trees dating to earlier cutting in 1905-10. Dominant tree species are sugar maple (*Acer saccharum* Marsh.), northern red oak (*Quercus rubra* L.), yellow-poplar (*Liriodendron tulipifera* L.), and basswood (*Tilia americana* L.). Average stand basal area in trees 1-inch and larger averages 128 ft^2/ac. Streambanks are well vegetated but considerable bare soil is still exposed at former skidroad crossing sites along the main stream. The predominant soil series on both WS1 and WS4 is Calvin channery silt loam (loamy-skeletal, mixed, mesic typic Dystrochrepts) with moderate erosion hazard (Losche and Beverage 1967). Soils are underlain with fractured sandstone and shale of the Hampshire formation.

Table 1—Characteristics of study watersheds

	Haddix	WS1	WS4
Area, acres	96	74	96
Aspect	S	E	SE
Average slope, %	40	40	25
Average stream gradient, %	11	16	13
Stream channel area, acres	.47	.26	.30
Sediment source area, acres[a]	10.8	3.0	1.1
Tree basal area, ft^2/ac[b]	109	109	154

S = South, E = East, SE = Southeast
[a] Defined as stream channel area + road area measured upon completion of logging.
[b] Basal area prior to harvest.

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The Haddix watershed supports a 12-year-old, mixed hardwood stand that originated after a 1986 harvest, along with older residuals left from earlier harvests. Approximately one-third of it contains a dense understory of rhododendron (*Rhododendron maximum* L.). After the harvest of 1986, it supported a mixed stand of oak species (*Quercus* spp.), hickory (*Carya* spp.), red maple (*Acer rubra* L.), and yellow-poplar, vegetation reflecting a somewhat xeric site. Residual basal area after the 1986 cut averaged 61 ft^2/ac, about half of the 109 ft^2/ac before harvest. The watershed is underlain by interbedded shale, siltstone, and sandstone of the Chemung geologic formation. The predominant soil series is Berks channery silt loam (loamy-skeletal, mixed, mesic, Typic Dystrochrepts), with moderate erosion hazard (Losche and Beverage 1967). Streambanks are generally well vegetated. The channel is armored with sandstone cobbles and gravel. However, as with many stream channels in the region, there is considerable bare soil along streambanks.

WS4 provided experimental control for water quality and streamflow. It has remained relatively undisturbed since about 1905 when much of the original timber was cut. Dominant tree species are yellow-poplar, sugar maple, and northern red oak, indicating a more mesic site than Haddix. In 1994, average basal area was 154 ft^2/ac for trees 1-inch dbh and larger. The stream channel is well armored with sandstone gravel and cobbles, and streambanks are well vegetated.

TREATMENTS

WS1 was commercially clearcut between May 1957 and September 1958. All merchantable trees >5.0 inches dbh were cut. Cull trees were left standing. An average volume of 8,984 bd ft/ac was harvested. Average basal area in trees >1-inch was reduced by 77 percent to 26 ft^2/ac. Logging was done with a tractor and arch, with no measures taken to protect soil and water resources. Skidroads were constructed on a logger's choice basis with no restrictions on road grade or location. For example, no culverts or bridges were used at stream crossing sites nor were normal post-logging practices such as waterbarring or seeding used. Many of the skidroads were in or immediately adjacent to stream channels (Fig. 1). There were no truck roads or landings located in WS1. Data for road area and location are in Table 2.

The Haddix watershed was cut to a 14-inch stump diameter between May 1986 and February 1987, removing an average volume of 5,344 bd ft/ac. Average basal area was reduced 44 percent in trees 1-inch and larger. A

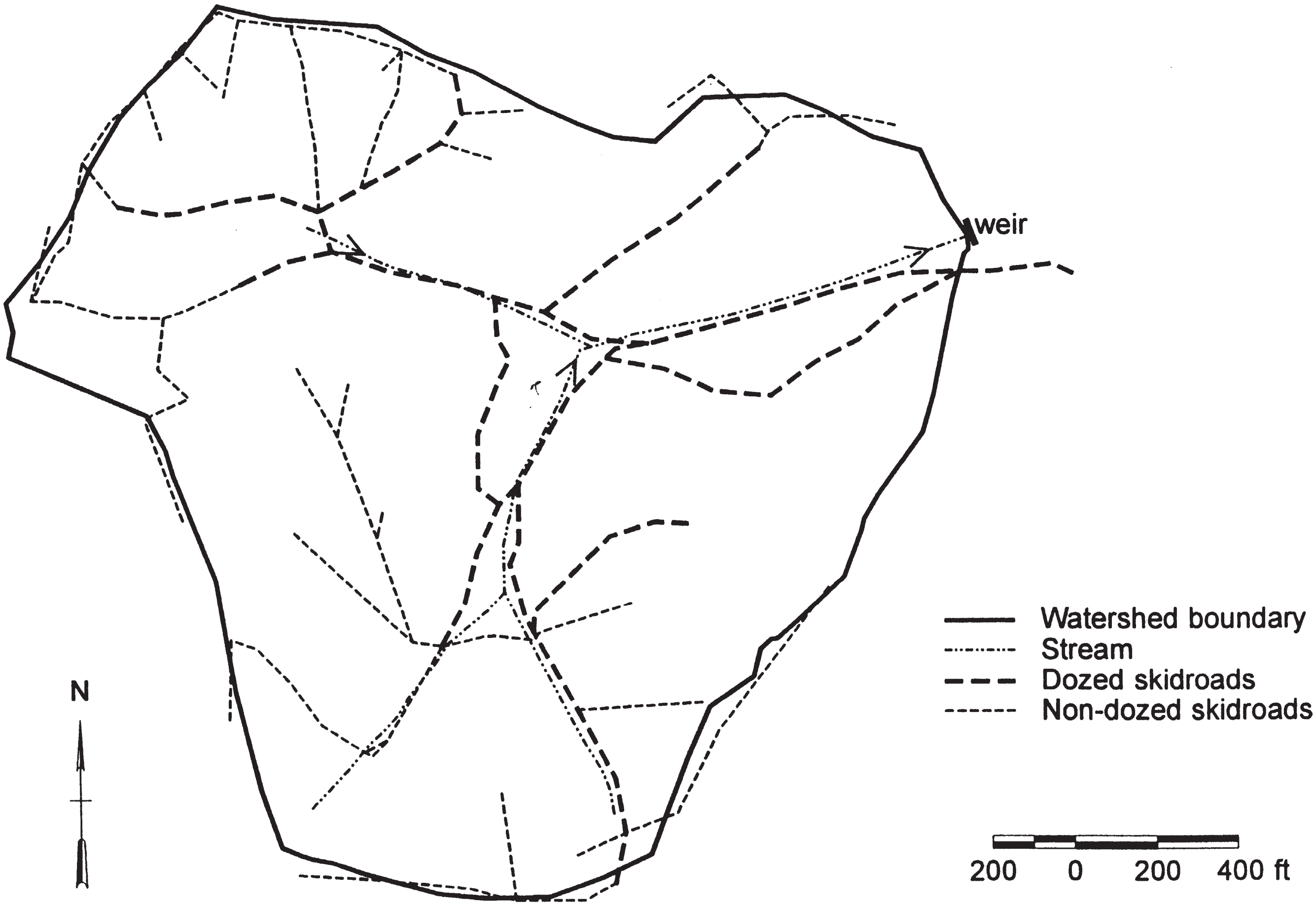

Figure 1—The unplanned road system in WS1 was used to remove 668 Mbf of timber from the 74-acre watershed. No measures were taken to protect soil and water resources.

Table 2—Roads in harvested watersheds

	WS1	Haddix
Dozed skidroads		
Length in miles	1.3	3.0
Area, acres	2.7	6.0
Percent of watershed area	3.6	6.2
By grade class, %		
0-10	22	74
11-20	32	24
21+	46	2
Within distance of stream, %		
<25 ft	40	1
<50 ft	61	3
<100 ft	66	3
Non-dozed skidroads		
Length in miles	2.2	0
By grade class, %		
0-10	31	0
11-20	35	0
21+	35	0
Truck roads		
Length in miles	0	0.9
Area, acres		4.3
Percent of watershed area		4.5
By grade class, %		
0-10	NA	100
11-20	NA	0
21+	NA	0
Within distance to stream, %		
<25 ft	NA	4
<50 ft	NA	5
<100 ft	NA	5

wheeled skidder was used to skid tree-length logs to landings. A D-4 bulldozer was used to construct skidroads as needed during harvesting.

BMPs recommended for use from 1979 to 1989 in West Virginia (West Va. Dep. Natur. Resour. 1979, 1982) were followed for this harvesting operation. The entire road system on Haddix was planned and laid out on the ground before logging to minimize roaded area and environmental impacts (Fig. 2).

A minimum-standard truck road (Kochenderfer and others 1984) was built with a John Deere 850 bulldozer. Broad-based dips (USDA For. Serv. 1940, Hewlett and Douglas 1968) spaced at about 150-foot intervals controlled overland flow. Natural grade breaks reduced the number of constructed dips needed. Except at stream crossings, roads were kept at least 100 ft slope distance from streams (Fig. 2). Metal culverts were installed at four locations where the truck road and skidroads crossed streams. A combination of metal culverts and ditches also was used on the truck road to drain three seeps. Culverts were left in place following the harvesting operation. All four landings were located on dry sites, at least 150 feet slope distance from the nearest stream.

Some rutting was tolerated on the ungraveled truck road, but hauling during extremely wet conditions was prohibited; it would have resulted in deep ruts and damage to the roadbed and water control features. Critical areas such as the two truck-road stream crossings were seeded with grass and slash was scattered on the roadfills immediately following road construction. Skidroads were smoothed and waterbarred at recommended spacing as logging progressed. Skidroads were limed, fertilized, and seeded with Kentucky 31 fescue using a cyclone seeder. In June 1987, the truck road and landings were disced, limed, fertilized, and seeded with a mixture of oats, clover, and Kentucky 31 fescue. Ground lime was applied at the rate of 3.0 ton/ac and 10-10-10 fertilizer at the rate of 500 lb/ac.

DATA COLLECTION AND ANALYSIS

Data collection began on WS1 and WS4 in May 1951 and in May 1982 on Haddix. Precipitation on each watershed was sampled by a network of recording and standard 8-inch gages. Streamflow was measured with 120° V-notch weirs on WS1 and WS4 and with a 3-foot H-type flume on Haddix. Each gaging site was equipped with an FW-1 water-level recorder. Water quality samples were collected by grab sampling above the gaging sites.

Harvesting effects on annual water yield and instantaneous peak flows were determined by using the paired watershed approach described by Hornbeck and others (1997). Since the purpose of the peakflow analysis was to compare the response of the watersheds to similar precipitation inputs, only storms for which the difference in precipitation did not exceed 0.3 inch were used to evaluate changes in peakflow. Linear regression was used to develop calibration relationships between water yield and storm peaks from WS4 and those to be harvested (WS1 and Haddix). After harvest, streamflow values from WS4 were inserted in the calibration equations to estimate what streamflow for the harvested watersheds would have been had they not been harvested. Differences between measured streamflow from the harvested watersheds and estimates of flow had they not been harvested were considered statistically significant and ascribed to forest harvest when the differences exceeded the 95 percent confidence intervals placed about the entire calibration regression.

Estimates of sediment export from WS1 and WS4 during the early 1957-58 logging period were based on turbidity and discharge measurements. Turbidities between 5-25 were determined by reference to standard suspensions in Nessler tubes and are termed Nessler turbidimeter units (NTU). Turbidities above 25 were measured with a Jackson turbidimeter and termed Jackson turbidimeter units (JTU), or filtered to determine suspended solids as parts per million (ppm).

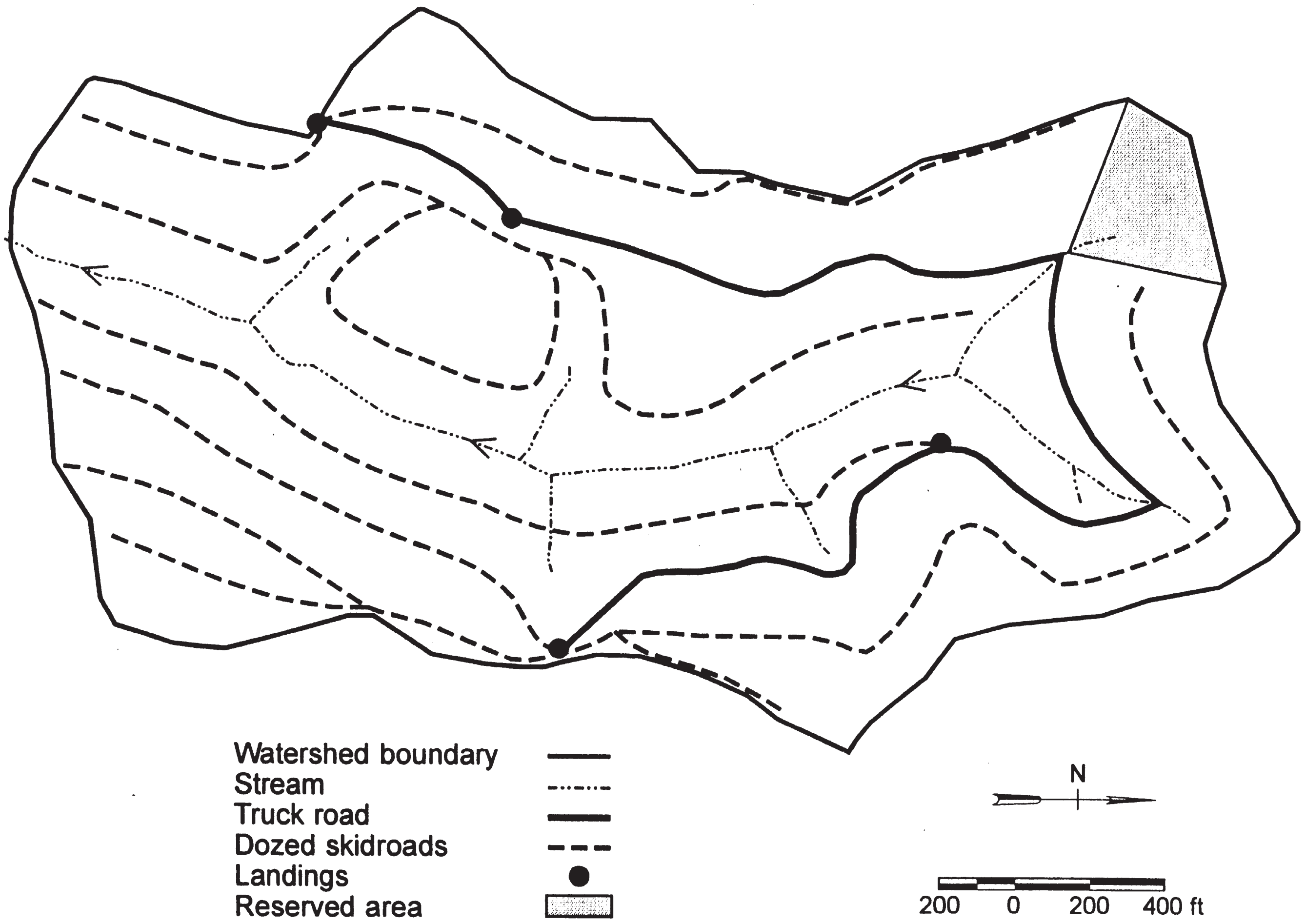

Figure 2—The road system in the Haddix watershed conformed to West Virginia's Best Management Practice Standards. It was used to remove 513 Mbf of timber from this 96-acre watershed.

During the 1982-1993 monitoring period each gaging site was equipped with a Coshocton wheel sediment sampler, which diverts 0.5 percent of the total flow into a storage tank. Two samples of tank contents were taken weekly, during base flow and before the tanks overflowed during storms. Tank contents were agitated vigorously while two 800-ml samples were drawn from spigots at the bottom of the storage tanks. Sediment produced during large storms was quantified by grab sampling and by automatic samplers. For each sample, turbidity was measured in NTU, then filtered to determine suspended sediment concentration in ppm.

Thermometers placed above the gaging stations in each watershed recorded weekly maximum and minimum stream temperatures. During the calibration period on WS1, stream temperatures were measured while collecting water quality grab samples. Beginning in May 1958, maximum-minimum thermometers were placed in the main stream above the gaging station. Water temperature records for 1958 are missing so temperatures observed during the 1959-60 period were compared with mean maximum temperatures observed during the 1961-73 period.

Grab samples for other criteria of water quality were collected weekly above the gaging stations on all three watersheds. In the beginning on WS1 and WS4, samples were analyzed for pH, alkalinity, and electrical conductivity. During the later period when Haddix was being logged, samples were analyzed for major ion concentrations at the Forest Service's laboratory. Analytical procedures and instrumentation information are given in Edwards and Wood (1993).

RESULTS AND DISCUSSION

Roads and Their Impacts

Roads and stream channels are major sources for stream sediment on the study watersheds. Road data for them are shown in Table 2. Road area was determined by length and width measurements from the top of road cuts to the toe of road fills after logging was completed. Haddix contained almost 4 times as much area in bulldozed roads as did WS1. However, when non-bulldozed roads are included, total road length in WS1 (3.5 miles) and Haddix (3.9 miles) are similar (Table 2). The differences in bulldozed road density are attributed to logging methods. The tractor and arch used on WS1 could negotiate fairly steep terrain without roads while the wheeled skidder used on Haddix was largely restricted to roads. Stream channel areas were similar among watersheds. They comprise a much smaller proportion of area than do roads in the logged watershed (Table 1), but are major sources of sediment in streams draining forested watersheds (Lull and Reinhart 1963, Patric 1976).

Area occupied by roads on the watersheds is decreasing as they revert to forest. Kochenderfer and others (1997) found that 6 years after logging, woody vegetation was dominant on half the original truck road area cleared in 1987. They concluded that reforestation should eventually reduce the original road prism area to less than half its original acreage. Several 12- to 16-inch yellow-poplar trees grow in the middle and on fill portions of skidroads in WS1.

Road grades are important from the standpoint of providing efficient access as well as soil and water protection. It is far more difficult to control erosion on steep roads, and they have less residual value for other uses once logging is completed. Roads of gentle grades, that are properly located and maintained, protect soil and water resources while providing effective access for many forest activities. Almost half of the dozed skidroads in WS1 had grades greater than 21 percent as opposed to only 2 percent of the roads on Haddix where BMPs were used (Table 2). Grades on 74 percent of the dozed roads on Haddix were in the 0-10 percent class while only 22 percent of the dozed skidroads on WS1 were in that class. All of the truck roads on Haddix fell into the 0-10 percent class.

The proximity of roads to streams is probably the single most important attribute that determines whether streams will be adversely impacted by timber harvesting operations. The importance of providing minimally disturbed protective zones between disturbed areas and streams has been recognized for a long time (Trimble and Sartz 1957, Lull and Reinhart 1963). Streamside protective zones are normally incorporated into state BMP guidelines. For example, West Virginia BMP guidelines recommend 100 feet protective zones on each side of perennial and intermittent streams and 25 feet for ephemeral streams (West Va. Dept. Natur. Resour. 1997).

There are striking differences between the unplanned road system on WS1 and the planned system on Haddix (Figs. 1 and 2). On WS1 many of the main skidroads were in or very close to stream channels. Sediment generated on roads was often carried by overland flow directly into streams. During storms, streamflow diverted into roads caused further excessive erosion (Lull and Reinhart 1963). On Haddix, the landings and contour road systems were at least 100 feet from streams except at crossing sites (Kochenderfer and others 1997). Machinery was not permitted off the road in streamside areas.

The distribution of bulldozed roads in relation to streams on WS1 and Haddix is quantified in Table 2. Forty percent of the dozed skidroads on WS1 were within 25 feet of streams (Hornbeck and Reinhart 1964) while only 5 percent of roads on Haddix watershed were that close. Sixty-one percent of the roads on WS1 were within 50 feet of streams as opposed to 8 percent on Haddix.

It is important to note that roads often generate more runoff than precipitation alone would indicate. Lull and Reinhart (1963) attributed this excess road runoff in WS1 to intercepted subsurface flow at road cuts. Kochenderfer and Helvey (1987), measuring soil losses from graveled and ungraveled road sections in central West Virginia, found that the percentage of annual precipitation measured as runoff ranged from 41.5 percent to 139 percent. Annual runoff exceeded precipitation on road segments with periodically active seeps.

Water Yield and Peak Flows

In addition to impacts of roads on overland flow, harvesting the forest reduces evapotranspiration and thereby increases water yield. The more intensive harvest on WS1 increased annual water yield 5.2 inches during the second year after harvest (Table 3). Increases disappeared quickly with regrowth and there were no statistically significant changes beyond the 6th year after harvest. Increased water yield was indicated after harvest on Haddix but was not statistically significant (Table 3).

Much of the increase in water yield occurs as augmentation to low flows during the growing season. Such increases result from increased soil water moving laterally through soil and bedrock to streams, thus having little impact on erosion. However, some peak flows also increased (Table 4). Some of the peak flow on WS1 also may have been caused by overland flow from poorly located skidroads (Reinhart and others 1963). Compared with Haddix, the lower residual basal area left after harvesting WS1 resulted in less transpiration and smaller soil water deficits, and thus greater overall increases in storm peaks (Table 4). The increases in peak flows are of interest in that they can cause additional erosion and sedimentation by scouring stream channels. However, the relatively small magnitude of the increases, plus the fairly rapid disappearance of increases with regrowth of the new forest (Table 4), suggests that harvests have minimal impacts on downstream flooding.

Sediment

Annual sediment yields and turbidity (Hornbeck and Reinhart 1964, Kochenderfer and others 1997) for WS1 and Haddix are shown in Table 5. During the logging operation sediment yield was 26 times greater on WS1 than on Haddix. These large differences reflect the characteristics of road systems discussed earlier. Although there was almost four times as much severely disturbed area on Haddix during logging, sediment yields were far less than those on WS1. The first year after logging they decreased to about 4 times more on WS1 than on Haddix and by the second year both returned to preharvest levels. Sediment yields were greatest during logging, when roads were repeatedly disturbed, then decreased rapidly after logging was completed. The rapid decrease in sediment yields on WS1 was attributed to vigorous regrowth and development of an erosion pavement on skidroads (Reinhart and others 1963). These soils contain about 50

Table 3—Impacts of harvesting on annual water yield

	WS1				Haddix			
Year after harvest	Actual flow	Estimated streamflow if unharvested[a]	Change due to harvest[b]		Actual flow	Estimated streamflow if unharvested[a]	Change due to harvest[b]	
	Inches	*Inches*	*Inches*	*%*	*Inches*	*Inches*	*Inches*	*%*
1	21.3	19.0	2.3[c]	12	28.0	24.2	3.8	16
2	31.6	26.4	5.2[c]	20	20.5	18.1	2.4	13
3	25.1	21.4	3.7[c]	17	28.9	26.7	2.2	8
4	27.5	24.0	3.5[c]	15	37.2	33.3	3.9	12
5	23.4	22.9	0.5[c]	<1	33.9	32.6	1.3	4
6	27.5	25.2	2.3[c]	9	20.2	19.0	1.2	6
7	23.5	23.6	-0.1	<1				
8	21.7	21.1	0.6	3				

[a] Determined from calibration regression.
[b] Determined by subtracting estimated streamflow from actual streamflow.
[c] Change exceeded 95 percent confidence interval about the calibration regression.

Table 4—Impacts of harvesting on instantaneous peak flows >3 ft^3/sec/mi^2 (c.s.m.)

	Growing season				Dormant season			
Year after harvest	No. of peaks (*n*)	Range in peak flows (c.s.m.)[a]	Statistically significant increases (*n*)	Average change	No. of peaks (*n*)	Range in peak flows (c.s.m.)[a]	Statistically significant increases (*n*)	Average change
				%[b]				*%*[b]
WS1								
1	3	20-28	2	69	12	4-77	6	18
2	7	4-14	1	27	18	3-23	8	18
3	0	–	–	–	2	4-21	1	45
4	1	25	1	46	10	4-52	4	26
5	5	4-31	1	9	7	4-70	4	18
6	0	–	–	–	8	5-30	0	–
Haddix								
1	0	–	–	–	7	3-25	1	42
2	4	11-78	2	76	8	10-46	0	–
3	2	14-63	0	–	6	7-48	2	35
4	2	18-27	0	–	9	4-33	0	–
5	1	16	0	–	11	6-31	0	–
6	0	–	–	–	8	6-26	1	36

[a] Estimated peak flows if watersheds not harvested.
[b] Average change for measured peak flows that were statistically significant.

Table 5—Annual suspended sediment yields and mean turbidity from WS1 and Haddix watersheds

	Sediment yields		Turbidity	
	WS1	Haddix	WS1	Haddix
	------ *Lb/ac* ------		*Ppm*	*NTU*
During logging operation	2,880	110	490	8.0
First year after logging	288	69	38	6.0
Second year after logging[a]	7	52	1	5.0

[a] Modern sampling techniques would probably have produced values for WS1 more comparable to Haddix.

percent stone fragments by volume and quickly developed a protective stone cover (Lull and Reinhart 1963).

While sediment yields temporarily doubled on Haddix, they remained within the range of 100 to 200 lb/ac/yr background levels expected from carefully managed forest in the eastern United States (Patric 1976). Sediment exports during a single large flood event on Haddix in 1985 (before harvest) were 2.8 times higher than annual sediment exports during logging. Others have observed that sediment exports are highly variable and related to the occurrence of individual large storms (Edwards and Owens 1991, Martin and Hornbeck 1994).

Careless logging on WS1 resulted in highly turbid water, averaging 490 ppm on WS1 during logging as compared to 8.0 NTU on Haddix (Table 5). The maximum turbidity observed during the logging on WS1 was 56,000 ppm (Reinhart and others 1963) while the maximum turbidity observed on Haddix was less than 100 NTU. Turbidity decreased rapidly on WS1, averaging 38 ppm during the first year after logging.

Water Temperature

Mean maximum growing season temperatures for selected periods are shown for all three watersheds in Figure 3. Highest temperatures usually coincided with low streamflow and high air temperatures during the July-September period. Water temperatures of 75°F are detrimental to brook trout (Embody 1921, Needham 1938). Reinhart and others (1963) concluded that the commercial clearcut on WS1 raised growing season maximum temperatures an average of 8°F during 1958-59, and reduced dormant season minima by 3.5°F. Heavy accumulations of slash covering the main stream channel might have moderated temperatures to some extent because Eschner and Larmoyeux (1963) reported that the highest temperature observed on WS1 (79°F) occurred in July 1959. Temperatures of 75°F and higher were observed several times on WS1 during 1959 but the highest observed in 1960 was 73°F. The highest temperature observed on WS4 during 1959 was 70°F and the maximum in 1960 was 65°F.

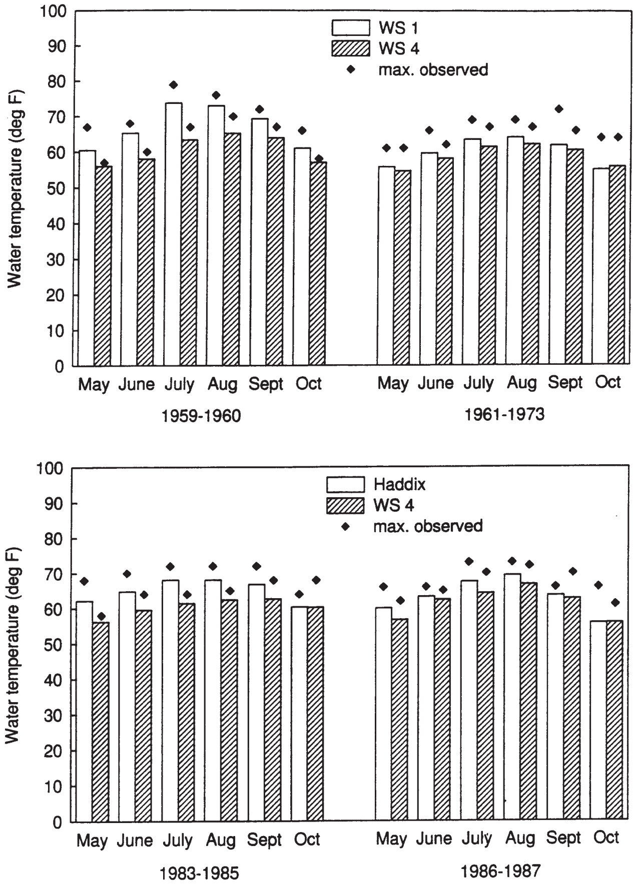

Figure 3—Mean maximum growing-season stream temperatures for WS1 (top) and Haddix (bottom) are compared with the control Fernow watershed (WS4).

Temperatures during pretreatment and logging periods on Haddix are very similar (Fig. 3). Kochenderfer and others (1997) concluded that diameter limit cutting on Haddix did not affect stream temperature because of shading by residual trees and understory vegetation. Although temperatures have consistently remained higher on the more xeric Haddix watershed, they have remained below 75°F.

Electrical Conductivity

Electrical conductivity, an index of total dissolved solids, decreased on WS1 following commercial clearcutting (fig. 4) and has consistently been higher on WS1 than on WS4. These differences probably reflect differences in geology and resultant weathering contributions to streams. There was a small increase in electrical conductivity in the Haddix stream after logging (fig. 4). An earlier study by Aubertin and Patric (1974) showed minimal streamwater ion increase after clearcutting Fernow watershed 3. Thus there

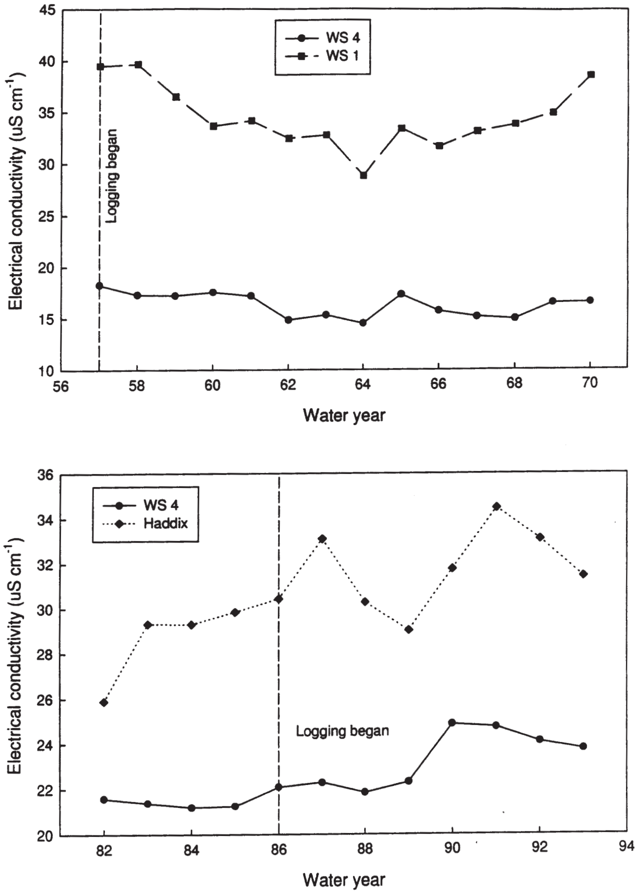

Figure 4—Time trends of electrical conductivity in streamflow from WS1 (top) and Haddix (bottom) compared with that from WS4.

is little reason to expect electrical conductivity in streams draining WS1 and Haddix to show much change after harvest.

SUMMARY

Our comparison of watersheds logged with and without BMPs clearly demonstrates their value. Logging without them on WS1 involved roads with unusually steep grades located close to or in streams, and no attempts were made to control water and revegetate the roads after logging. The result was significant erosion and sedimentation with increased stream temperatures. In contrast, careful adherence to West Virginia's BMPs when logging Haddix, resulted in only minor changes in sediment and water temperature. The changes were within background levels, clearly illustrating that harvesting operations utilizing BMPs will protect water quality.

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HARVESTING STRATEGIES FOR INCREASING THE AVAILABILITY AND QUALITY OF HARDWOOD FIBER

Chris B. LeDoux[1]

Abstract—Worldwide demand for wood and wood products will continue to increase as global human population increases. These increasing demands for wood will continue to provide economic incentives for non-industrial private forest-land (NIPF) owners to increase the availability and quality of wood fiber harvested from their lands. The challenge is to encourage and facilitate NIPF owners and other commercial forest industries to support these demands without compromising their own short- and long-term economic and other ownership goals.

Over the years silvicultural researchers have developed methods for growing quality trees faster and in more ecologically, environmentally, and socially acceptable ways. Simultaneously, harvesting researchers have developed an enormous database on alternative logging technologies to harvest timber in economically and environmentally acceptable ways. This study demonstrates that integrating what we know about growing trees with what we know about harvesting them can increase the availability of wood fiber and add value to future crops.

Results for the oak/hickory forest type in West Virginia show that up to 1,736.61 ft^3/acre of wood fiber can be harvested 10 years sooner than usual by simply matching size of machine to wood harvested. Specifically, the study focused on the gains that can be made by matching size of machines to size of wood harvested, by utilizing harvesting machines better and more efficiently, and by training machine operators to be more efficient. Gains of up to 40 percent in present net worth can be attained by early thinning of a stand when harvesting machines are matched to wood size harvested. Results of the study benefit loggers, planners, managers, forest industry, NIPF owners, and society in general.

INTRODUCTION

As global human population increases, worldwide demand for wood and wood products will continue to increase. Because the majority of the hardwood forested land in the United States is owned by non-industrial private forest-land (NIPF) owners (Birch 1996), they will be asked to increase the availability and quality of wood fiber harvested from their lands. The challenge for forest industry and NIPF owners is to meet these demands while simultaneously meeting their own short- and long-term economic and ownership goals (Sampson 1996). Another challenge is to communicate the silvicultural and harvesting technology advances to the forest industry and NIPF owners so they can continue to provide wood products to society in a sustainable manner over time (Cantrell 1996).

Researchers have accumulated volumes of knowledge about how to regenerate and grow trees (Smith and others 1988). We know a great deal about how different species of trees respond to alternative silvicultural treatments. Stocking guides have been developed to maximize tree growth for selected species (Lancaster and Leak 1978, Sampson and others 1980). Over the same time, research in logging methods has been accumulated on production, cost, and applicability for a wide range of cable logging (LeDoux 1985), ground-based (Huyler and LeDoux 1989) and cut-to-length/forwarding machines (Huyler and LeDoux 1996). Harvesting studies in clearcuts, thinnings, shelterwoods, and group-selection applications (LeDoux and others 1991, LeDoux and others 1993) evaluate these different processes and silvicultural systems. We know a great deal about how to regenerate, grow, and harvest trees in environmentally acceptable ways. The need is to integrate what we know about silviculture with what we know about logging technology and then to get the information to loggers, land managers, forest industry, and NIPF owners.

METHODS

Description of ECOST Version 3 and MANAGE

ECOST Version 3 and MANAGE were the models used in this study. ECOST Version 3 is a stump-to-mill logging cost-estimating model for Eastern hardwoods. ECOST Version 3 allows for the stump-to-mill cost estimation for cable and ground-based systems. The difference from previous versions is that it includes skidding cost and production functions for four small farm/skidding tractors and for three skidders with small, medium, and large capacity. Specifically, ECOST Version 3 allows the user to estimate the felling, bucking, limbing, yarding/skidding, loading, hauling, and unloading costs for several cable yarders, small tractors, and skidders. The costs can be estimated in components or as stump-to-mill for most conditions loggers will encounter when logging Eastern hardwood stands.

MANAGE (LeDoux 1986), a computer program written in FORTRAN V, integrates harvesting technology, silvicultural treatments, market price, and economic concerns over the life of a stand. The simulation is a combination of discrete

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and stochastic subroutines. Individual subroutines model harvesting activities, silvicultural treatments, growth projections, market prices, and discounted present net worth (PNW) economic analysis. Specifically, the model allows the manager to evaluate how alternative harvesting technology, silvicultural treatments, market price, and economic combinations affect costs and benefits over the life of a stand. The model uses a detailed, individual user-specified tree list and then projects stand growth based on some user-specified silvicultural treatment, harvests the desired volume or stems with the logging system specified, sells the wood, and conducts economic analysis for the respective treatment and entry. MANAGE was run for a stand in the oak-hickory forest type with alternative combinations of logging technology.

Using ECOST Version 3, the user obtains information on skidding costs for alternative logging machines and for any set of silvicultural/stand conditions. Using MANAGE, the user can project the costs and benefits of alternative combinations of silvicultural treatments and logging technology for any stand of interest.

Harvest Treatments

The harvesting treatments evaluated include no thinning and an area-wide low thinning that removed all trees below an average dbh of 12 inches. The objective for each thinning treatment was to leave the larger crop trees in order to grow quality wood products for the final harvest. The wood harvested was sold as pulpwood and sawlogs. The stand was logged with ground-based logging technology. Specifically, the stand was logged with a JD 440C, JD 540B, and a JD 640D skidder. The John Deere machines are all articulated frame, four-wheel drive cable skidders manufactured in the United States. The John Deere 440C is a 70-horsepower skidder, the 540B is 90-horsepower, and the 640D is 120-horsepower. These three machines are representative of the types of cable skidders found on logging jobs in the Eastern United States.

Site and Stand Conditions

In this study, the stand chosen for demonstration is from the oak/hickory forest type in West Virginia and represents 2,971 acres in total land area. The species mix includes northern red oak (*Quercus rubra* L.), American basswood (*Tilia americana* L.), white ash (*Fraxinus americana* L.) , and black cherry (*Prunus serotina* Ehrh.). The average site index of the stand is about 70. The stand is 60 years old and contains 257 trees per acre that are more than 5 inches dbh. The stand has an average tree dbh of 11.13 inches and about 4,412.42 ft^3/acre of merchantable volume. The land is located on gentle to moderate slopes and requires ground-based systems for harvesting. It is assumed that new road construction is not required. The stand is located 25 miles from a pulpmill/sawmill.

RESULTS

Matching Machines to Wood Size

The thinning was simulated at different stand ages using JD 440C, JD 540B, and JD 640D skidders. The resulting delay-free skidding costs were graphed by machine and the average stand diameter at each age (Fig. 1). The cost curve for the JD 440C is truncated at 12.2 inches because turns containing multiple logs of this tree size exceed the capacity of the machine. At a stump-to-road cost of \$0.20/ft^3, the JD 440C would breakeven when operating in stands that average 6.6 inches dbh. The JD 540B would breakeven in stands that averaged about 8.5 inches, and the JD 640D would breakeven at average dbh of about 9.1 inches. By matching the smaller, less expensive skidder with younger stands, the manager/logger can enter younger stands earlier to conduct the thinning. Using a larger machine such as the JD 640D for the thinnings would require that the stand contain bigger trees before reaching breakeven conditions (Fig. 1). Matching skidding machines to tree size could allow managers/loggers to enter younger stands and capture all the benefits of thinning and yet breakeven. Matching the size of machine to the size wood harvested also makes the wood from the thinnings available to fiber markets earlier in the life of a stand and increases the availability of wood fiber to markets.

Impact of Utilization Rate on Entry Timing

Clearly, few logging operations/machines operate in delay-free environments. Delays range from total machine malfunction resulting in a major breakdown/delay to the machine operator taking too many breaks or failing to service the machine. The thinning was simulated at different ages with a JD 540B skidder at utilization levels of 90, 80, and 60 percent (Fig. 2). Utilization rate is measured as the percentage of working time that the machine is actually being used in a productive mode as opposed to being non-productive while in a delay mode. A machine with a high utilization rate will generally produce more wood volume/unit time and cost less/unit produced than the same machine at a lower utilization rate. For this study, at a cost/ft^3 of \$0.20, the JD 540B at 90 percent utilization would breakeven while operating in stands that averaged about 11.5 inches dbh. For the same machine

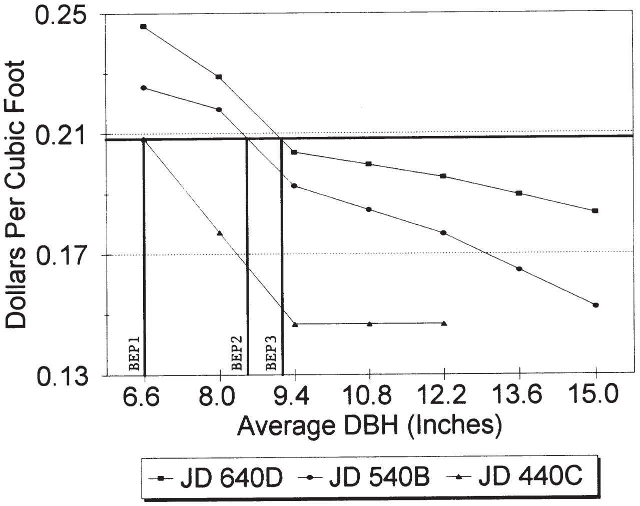

Figure 1—Simulated delay free skidding costs for JD 440C, JD 540B, and JD 640D skidders by average stand dbh (BEP = breakeven point).

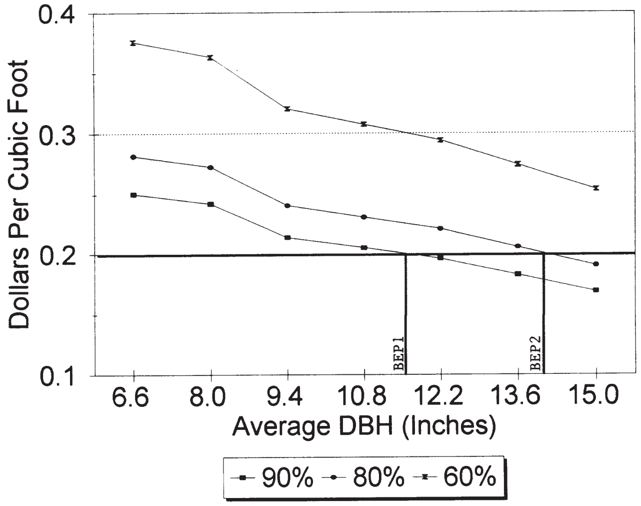

Figure 2—Simulated skidding costs for JD 540B skidder at three utilization levels by average stand dbh (BEP = breakeven point).

and conditions, but at an 80 percent utilization rate, the breakeven point occurs at about 14.0 inches dbh. At a utilization rate of 60 percent, the JD 540B would not breakeven. Operator training strategies to increase the utilization rate of machines can allow managers/loggers to operate in younger/smaller dbh stands, thus making wood fiber available to wood markets earlier in the life of a stand.

Impact on Rotation Age and Wood Quality

The advantages of entering a stand earlier in its life by matching machine size to wood size were further studied by inputting the costs from Figure 2 at the 90 percent utilization level into the MANAGE model. Initially, the stand was not thinned and was projected to its Optimal Economic Rotation Age (ORA). The stand was then thinned using a JD 440C and a JD 540B skidder at the earliest age possible that would result in an economic/breakeven entry to illustrate the impact of matching machines to wood size on rotation age, financial returns, and resulting quality development. The stand was thinned at age 60 with the JD 440C. The stand was thinned at age 70 with the JD 540B because of the higher skidding costs. The thinned stands were then projected to their ORA. The delivered product prices used in this study by species and log quality are shown in Table 1. The results from simulations for the no-thin and thinning treatments with MANAGE are summarized in Table 2. Matching machine size (JD 440C) to wood size would allow the stand to be thinned at age 60 yielding 1,736.61 ft^3/ac of wood fiber. Under the same conditions but thinning the stand at age 70 (with JD 540B), the yield is 1,484.97 ft^3/ac. Using the smaller skidder and thinning all 2,971 acres could yield 5.1 million ft^3 of wood fiber that would be economically available 10 years earlier than if a larger skidder were used in the first thinning. The thinnings do not produce more volume overall, they just make fiber available earlier.

Table 1—Delivered log prices by species and grade, International 1/4-inch (Worthington and others 1996)

Species group	Grade 1	Grade 2	Grade 3	Pulpwood
	- - - - - - - *$/mbf* - - - - - - - -			*$/Cord*
Red oak	561	397	225	40
Basswood	321	239	143	40
Black cherry	571	400	259	40
Ash	420	297	169	40

Table 2—Simulated results by size of skidding machine

Machine	JD 440C	JD 440C	JD 540B
Thinning age (yrs)	No thinning	60	70
Avg. stand d.b.h. (in)	-	8.78	9.13
Trees cut/acre	-	172	134
Vol. removed/ac(ft^3)	-	1736.61	1484.97
Present net worth (PNW-$)[a]	-	38.28	9.11
Cash flow/ac. ($)	-	38.28	12.24
Optimal rotation age (ORA, yrs)	90	100	110
Ave d.b.h. at ORA (in)	14.03	20.32	20.12
Vol/acre at ORA, ft^3	5507.94	4355.94	5047.51
Total vol/acre removed, ft^3	5507.94	6092.55	6532.48
PNW/ac at ORA ($)[b]	1360.67	1872.98	1614.78
Cash flow/ac at ORA ($)	3302.70	6109.72	7079.05

[a] Real discount rate = 3 percent.

[b] Discounted to age 60.

The unthinned stand reached its ORA at 90. The thinned 60-year-old stand would reach its optimal rotation 10 years sooner than if the stand were thinned with the larger skidder at age 70. Both thinned stands would produce wood that would average 20+ inches dbh compared to 14+ inches in the unthinned stand. The larger 20-inch dbh trees would yield higher quality logs than those from the 14-inch stand. Since the thinned 60-year-old stand reaches optimal rotation sooner than the thinned 70-year-old stand, the present net worth (PNW) is $1,872.98 compared to $1,614.78, or an increase of 15.99 percent. This could represent a gain of $853,776.27 in cumulative PNW over the thinned 70-year-old stand if all 2,971 acres were thinned at one time. It is unlikely that all 2,971 acres would be thinned at one time, but for this analysis it demonstrates the potential volume and financial yields possible. The thinned 60-year-old stand produces a cumulative PNW increase of $550.59/acre compared to the nonthinned stand. Although the thinnings do not produce more volume overall, they serve to concentrate the remaining volume on fewer stems but of higher quality.

CONCLUSIONS

Matching machine size to size of wood harvested results in wood fiber available earlier in the life of the stand, shorter ORA for similar size products, and significant gains in PNW—up to 16 percent. Strategies to improve machine utilization also allow managers/loggers to enter stands earlier making wood fiber available earlier and improving the quality/adding value to the future stands. In addition, the combination of carefully matching the size of machines to the size of wood harvested and implementing strategies to reduce skidding delays allows managers/loggers the same benefits. Up to 1,736.61 ft^3/acre of wood fiber can be made available sooner by simply using smaller, less expensive skidders to enter the stands at earlier ages. Thinned stands produce larger dbh/higher quality wood and, thus, larger economic returns compared to unthinned stands. Gains of up to 40.46 percent in discounted cumulative PNW can be realized by early thinning versus no thinning.

In this study, we did not consider the impact of residual stand damage on financial yields over time. We have found that residual stand damage from thinnings can range from none to very high levels. The impact of residual stand damage is best dealt with on a case-by-case basis. Although most NIPF owners own tracts substantially less than 2,971 acres, the results are applicable to small tracts as well. The increased availability of wood fiber along with the value added in quality to the future stand will help meet the world's demand for fiber and quality hardwoods.

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