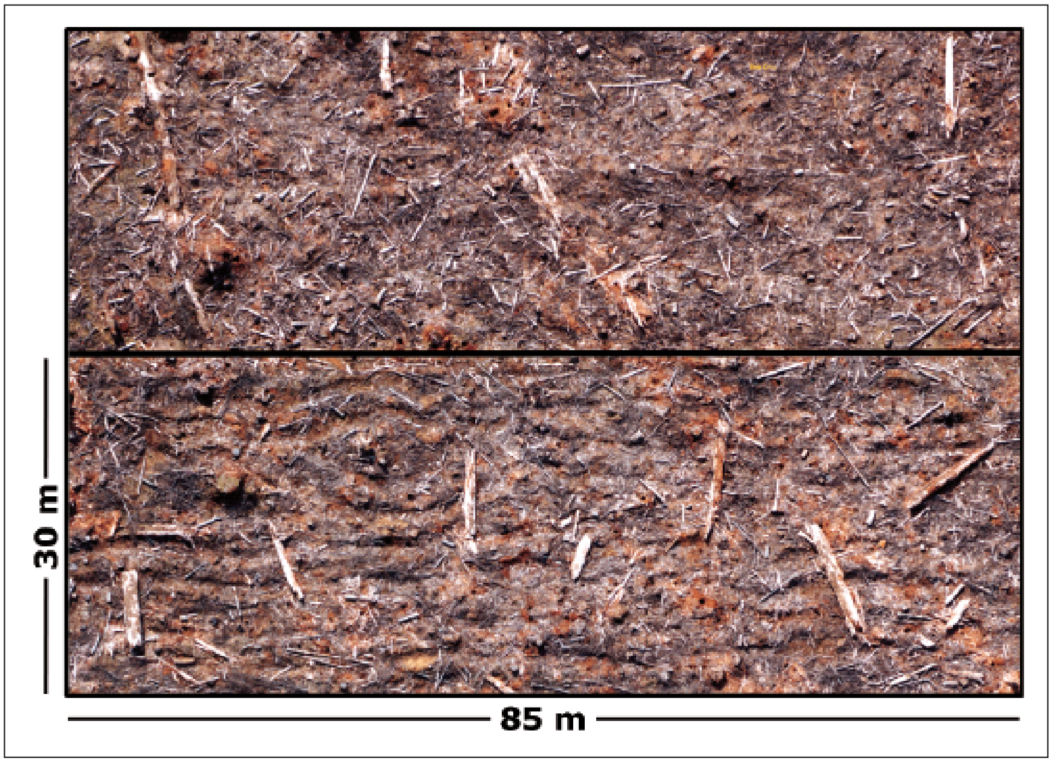

Figure 13—Aerial views of plots after cable (top, no traffic lanes visible) and ground-based harvesting (bottom, traffic lanes visible along the main plot axis) at the Fall River research area.

Postharvest Biomass and C and N Stores

Methods

Coarse woody debris—

We measured residual CWD in one randomly chosen plot from each of the four cable-yarded biomass-removal treatments within each block from February to May 2000. We tallied CWD by using the line-transect method (Brown 1974, Harmon and Sexton 1995). As in the preharvest assessment, plots were divided into five equal sections (17 by 30 m), and two randomly located 10-m transects were surveyed in each section, resulting in a total transect length of 100 m per plot. Transect lengths were not adjusted by slope because slopes were short and < 15 percent. The starting point for each transect was a randomly-located coordinate. Transect direction was determined by random compass bearings from 1° to 360°. Transects that would have extended outside the plot were ended at the plot border, and then extended back into the plot from the origin in the opposite direction (180°) to result in the correct length. Transects were allowed to extend into adjoining subplot sections.

Figure 14—Tillage with an excavator in plots with soil compaction (top), and traffic lanes before (bottom left) and after tillage (bottom right) at the Fall River research area.

Woody residues were subsampled by size class. Residues with diameters from 0.6 to 2.5 cm were measured along the first 1 m of each transect; residues with diameters from 2.5 to 7.6 cm were measured along the first 2.9 m; and residues with diameters greater than 7.6 cm were measured along the entire 10 m of the transect. Diameters were measured at the point of intersection of the transect with the measured residue piece, and perpendicular to the piece's longitudinal axis.

We classified decay classes of CWD according to Maser et al. (1988) (table 18). No attempt was made to distinguish between classes 1 and 2 because the harvesting treatments were completed 8 to 10 months before sampling. Coarse woody debris from recently harvested trees was classified as class 2 if limbs were present, foliage was not evident, and wood was discolored but firm. Decay class 5 material, commonly referred to as "red rot," was not determined on line transects but was included with the forest floor component. We did not attempt to classify woody material by plant species.

Volume of woody debris (VWD, m^3/m^2) found on line transects was calculated by using the equations in Harmon and Sexton (1996):

For debris diameters ≤ 7.6 cm $$VWD = 9.869 \times N_o \times a \times (d^2/8L) \quad [4]$$

For debris diameters > 7.6 cm $$VWD = 9.869 \times N_o \times (d^2/8L) \quad [5]$$

where

N_o = the number of pieces of the given size class intercepted by the transect, a = average secant for pieces (adjustment for nonhorizontal orientation of pieces), d = average diameter in meters for pieces ≤ 7.6 cm, or actual diameter in meters for pieces > 7.6 cm, and L = length of transect (m).

The computed volumes were summed by size class to yield CWD volume by plot. These volumes were then multiplied by wood density to determine wood mass. Wood density was determined from additional samples collected 4 to 6 months after the line-transect survey was finished. We collected four to seven samples per plot on the transects in each of the following diameter ranges (in centimeters): 0.6-2.5, >2.5-7.6, and >7.6-60 for decay classes 1+2, 3, and 4, with the exception of the smallest size class in decay class 4, which was not encountered. Methods for sampling old-growth logs for wood density and C and N concentrations are described in the next section. Half of these CWD samples were collected in blocks I and II, and half in blocks III and IV. This block grouping reflected different proportions of Douglas-fir to western hemlock basal areas in each block (Terry et al. 2001). Samples for density determination were collected from two 10-m line transects across selected treatment plots. Line transects were initiated at a random starting point 2 m inside plot borders along the south boundary, and extended across the plot at a 90° angle. Decay class 2 samples were collected from the BO and BO5 plots, which had more residual material than the other treatments. Classes 3 and 4 were collected from TT and TT+ plots. This scheme was designed to allow easy access to debris of specified decay classes. For diameters and decay classes not found in the transects, the given plot was systematically traversed to find the samples needed. Caution was taken not to collect two samples directly adjacent to one another along the traverse line to ensure spreading the samples out across the test area. On several occasions other plots (BO5) in each block were systematically traversed to acquire the samples not found in the bole-only plot within a block.

Small pieces were cut with hand-pruners or loppers into 10-cm-long sections, and protruding twigs were trimmed. Larger pieces were cut with handsaws and chainsaws into about 10-cm-thick disks. Diameter of each 10-cm disk was measured at both ends and in the middle, and thickness was measured in four quadrants of the disk to get an average. These measurements were used to obtain volume assuming a cylinder shape. Disks from the large pieces were quartered with an axe into wedges and then submerged in water until air bubbles subsided. Volume was obtained from the weight of displaced water. Most pieces, including those in decay class 4, held their form enough to obtain volume. All samples were oven dried at 70 °C until constant weight. Wood density was averaged for blocks I and II, and blocks III and IV, and for the diameter classes described in line transects. There were eight samples per block-group and diameter class. We used N and C concentrations by decay class for branch and wood material collected from the preharvest tree biomass and CWD assessments to determine C and N stores as described in previous sections.

Old-growth legacy wood—Old-growth logs greater than 60 cm in diameter were sampled in January 1999 before harvest for determination of wood density, and C and N concentration. At least four random transects were located in each block and the closest old-growth log was chosen as the sample log. Three to five logs were sampled per block. Each log was classified as decay class 3, 4, or 5 (table 18). A 9- to 13-cm-thick wedge extending to the center of the log was cut from the upper to middle log section with a chain saw. Volume of the wedge was determined by measuring the angle (generally less than 90°), the thickness at two places along each cut side and around the uncut edge, and the wedge radius (r), averaged from three readings along the cut side and in the middle. Volume of the wedge (Vw; m^3) was calculated from these measurements as:

$$\mathrm{Vw} = \mathrm{angle}/360\ (3.1416\ r^2 \times \mathrm{thickness}) \qquad [6]$$

Wet weight of the wedge was determined in the field, and a subsample of the wedge was taken to the laboratory to determine oven-dry weight. Subsamples were stored in zip-lock bags in a cooler until oven-drying. We used the C and N concentration values for CWD decay classes in the preharvest surveys for all nutrient calculations in the posttreatment surveys. Analyses were conducted at the University of Washington Analytical Services Laboratory as described previously for other woody debris.

Stumps—

Volume of the aboveground portions of stumps from the recent harvest was determined per block. Diameter of the fresh-cut face of each stump was measured with calipers in two perpendicular directions. Root-collar-diameter was measured with a diameter tape at the lowest point on the stump above the swelling associated with roots close to groundline. We then measured height from the root collar to the cut-face along two sides. Diameters of the root collar and the cut-face were averaged to calculate stump volume assuming that stumps were cylinders. Volume was multiplied by wood density of class-2 woody debris to estimate stump mass. To estimate stump C and N contents, mass was multiplied by concentrations of C and N from class-2 woody debris (fig. 9).

Forest floor—

Forest floor was assessed along the same transects used for CWD determinations. At approximately 2, 4, and 6 m along each transect, we described forest floor condition, depth, and cover area in a 0.5- by 0.5-m metal frame. Stumps and old-growth logs were avoided, and the forest floor area was adjusted accordingly because the area occupied by these components had been previously assessed. Additionally, we surveyed the forest floor beneath slash in the BO and BO5 treatments. Slash had been removed in TT and TT+ treatments, allowing an unobstructed view of the forest floor and soil surface. At approximately 8 m along each line transect, the metal frame was positioned and forest floor was collected to determine dry weight. After the frame was positioned, we used hand pruners and chain saws to cut woody material along the frame borders. Forest floor of each class found within the frame was collected separately. Coarse woody debris > 0.6 cm in diameter was accounted for in the line transects; this material was set aside. All smaller woody and forest floor materials down to mineral soil were excavated and collected. Often, larger sized woody materials were buried beneath a layer of needles or disturbed soil on the surface. These woody pieces, regardless of size, were collected to a depth where mineral soil was reached. Samples were dried at 70 °C to constant weight.

To determine specific gravity of red rot, 20 additional red-rot samples were collected close to the plot borders in areas previously not sampled. A straight, narrow shovel was inserted into the red-rot sample. A piece of plywood (14 by 40 cm) was inserted behind it, and the shovel was removed. Three more pieces were inserted, each at 90° to the previous piece, with their edges touching to form a square sample “box.” Red rot was transferred from inside the square to a paper bag, and the dimensions of the excavation were recorded for volume calculations. Depending on depth, one to three bags per square were necessary. The shallowest sample was 12 cm, and the deepest was 64 cm. For depths greater than 40 cm, shovel and plywood pieces were used as described to extend depth. Red rot samples were dried at 70 °C to constant weight, and density was calculated as dry weight per unit volume. Even though red rot extended almost twice as deep into the soil in BO and BO5 than in TT and TT+ treatments, the density of the red rot material by depth or treatment was not statistically different; therefore, an average of all samples (0.15 Mg/m^3) was used for mass calculations. The total mass of red rot per plot was obtained by multiplying plot cover of individual sampling points in square meters by depth and density.

Total area used for forest floor and red rot mass calculations was reduced by percentage of area covered by stumps, old-growth logs, and large CWD pieces. The percentage of area covered by fresh and old-growth stumps, and remnant old-growth logs was determined by surveying one randomly chosen BO, TT, and TT+ plot within each of four blocks during July 2001. We placed a 1- by 1-m frame divided into 16 equal sections in the four quadrants around each of 30 trees per plot using the tree location as the plot center. Trees were selected by having a random start on one of the first five seedlings in the first measurement plot row, then alternately sampling every 5th, then every 6th tree, down the row. Area of stumps, old-growth logs, and forest floor around individual seedling were estimated to the nearest 1/2 square (1/32 or 3 percent) per 1-m^2 grid. This area averaged 7.4 percent in BO, BO5, and TT, and 2.4 percent in the TT+ treatments. The main objective of this survey was to permit assessment of seedling performance in the different forest floor conditions. The area covered in stumps and old-growth logs was likely underestimated, because planting locations were moved when pin-flag location landed on these obstructions.

Forest floor samples were dried, weighed, and chipped with a Yard Shark™ chipper/shredder (Tilton Equipment Co.). Forest floor materials were pooled by plot and forest floor class. Samples were thoroughly mixed on a tarp, arranged in a square and divided into fourths; two diagonal parts were kept for nutrient analysis; the rest of the material was stored. Nutrient analysis was also done on treatment-level composites created by mixing 50 g of sample from each plot for class 2 and for class 4. Forest floor class 5, bare soil, was not analyzed for nutrient concentration because it is not organic forest floor.

Total C and N concentrations were determined at the University of Washington Analytical Services Laboratory as described above. A subset of samples were analyzed by using the same methods at the Weyerhaeuser Analytical Laboratory for cross-checking.

Carbon and N stores—

We determined nutrient concentrations in samples of forest floor conditions 1 through 7 composited by plot. Total C and N were determined at the University of Washington Analytical Services Laboratory. A subset of samples were also analyzed at the Weyerhaeuser Analytical Laboratory for cross-checking. Carbon and N concentrations were multiplied by the mass of the corresponding organic matter type to calculate C and N stores. For old-growth logs, we used mean values weighed by the relative abundance of old-growth logs by decay classes determined in the preharvest sampling, as C and N concentrations changed with decay class. Masses of individual organic matter components and N pools were added to determine plot-level totals.

To determine C and N pools, we used C and N concentration values determined from the preharvest woody debris samples for material >7.6 cm diameter in similar decay classes (fig. 9). For the material in classes 1, 2, and 3, and 0.6- to 7.6-cm diameters, we used C and N values determined from the preharvest stand biomass sampling of live and dead limbs. The same C and N values for class 4 material were used for all diameter classes (fig. 9). For old-growth stumps and snags, we used C and N concentrations determined for old-growth logs by decay class. The C and N values for old-growth logs were weighted by the proportion of old-growth logs in each decay class in each block.

Results

In general, wood density decreased with decreasing diameter and with increasing degree of decay. Wood density of CWD ranged from 0.14 g/cm^3 in decay class 4 for the >2.5- to 7.6-cm-diameter material to 0.41 g/cm^3 in decay classes 1+2 in the >7.6 to 60.0-cm-diameter material (table 24). The average wood density in g/cm^3 for old-growth logs by decay class was 0.38 for class 3, 0.20 for class 3.5, 0.16 for class 4, and 0.14 for class 5.

Biomass of CWD, old-growth logs, and recent stumps after treatments ranged from 8 Mg/ha in TT+ to 135 Mg/ha in BO with a clear trend toward less residue mass as the intensity of biomass removals increased (table 25). Decay class 2 mass showed the same downward trend with increased biomass removals (i.e., BO > BO5 > TT > TT+) as expected. Recent stumps added approximately 5 Mg/ha in each treatment. Old-growth logs were the largest mass of woody debris in all treatments except TT+ where they were removed as part of the treatment specifications. Decay class 4 was a small component of coarse woody debris (excluding old-growth logs and stumps) in all treatments, averaging less than 0.5 Mg/ha in each. Carbon and N concentrations for CWD 0.6- to 7.6-cm diameter in decay class 1 and 2 were 49.4 and 0.22 percent, respectively, and in class 3 were 48.8 and 0.17 percent, respectively. Average old-growth log C concentrations were 49.8 percent in decay class 3, and 52.5 percent in classes 4 and 5. Average N concentrations were 0.13 and 0.28 percent for old-growth logs in class 3, and classes 4 and 5, respectively. Overall, average C and N concentrations for old-growth logs weighted by decay class and diameter were 50.4 and 0.17 percent, respectively. The N concentration for old-growth logs is relatively low compared to small CWD of similar decay class (fig. 9) because of the amount of solid wood still remaining in the center of many of these logs.

Carbon and N stores in CWD for the four treatments followed a similar trend as observed for biomass (i.e., BO, BO5 > TT > TT+) (table 26). Carbon stores combining CWD, old-growth logs, and recent stumps ranged from 4 to 67 Mg/ha, and N stores ranged from 8 to 210 kg/ha.

Table 24—Wood density by decay class for coarse woody debris and old-growth logs after forest harvesting at Fall River

Class	Wood density by log diameter class (cm)			
	0.6-2.5	>2.5-7.6	>7.6-60.0	72-115
		Mg/m^3		
1+2	0.28 (0.01)	0.29 (0.02)	0.41 (0.01)	
3	.22 (.01)	.22 (.01)	.35 (.01)	
4		.14 (.01)	.25 (.05)	
Old-growth logs				0.291[a] (.08)

Values are means with one standard error in parentheses. The number of observations (n) ranged between 6 and 27 samples for diameter classes between 0.6 and 60.0 cm, and 17 samples for the 72- to 115-cm class.

[a] Wood density weighted by the biomass of old-growth logs in each decay class across four blocks.

Table 25-Coarse woody debris biomass[a] after forest harvesting at Fall River

Treatment	Biomass by decay class					
	1+2	3	4	Old-growth logs	Recent stumps	Total biomass
	Mg/ha					*Mg/ha*
Bole only	49.8 (6.9)	10.1 (3.0)	0.1 (0.1)	70.0 (29.5)	5.2	135.2
Bole only to 5-cm top	27.3 (2.6)	10.0 (3.4)	0	76.3 (36.2)	5.2	118.8
Total tree	10.7 (2.4)	8.8 (5.0)	.5 (.5)	27.9 (9.5)	5.2	53.1
Total tree plus	1.9 (.9)	.3 (.1)	.2 (.2)	0	5.2	7.6

Values are means with one standard error in parentheses (n = 4 plots).

[a] Excluding old-growth stumps and snags.

Table 26—Carbon (C) and nitrogen (N) stores in coarse woody debris[a] after forest harvesting at Fall River

Treatment	CWD by decay class											
	1+2		3		4		Old-growth logs		Recent stumps		Total	
	C	N	C	N	C	N	C	N	C	N	C	N
	Mg/ha	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*
Bole only	23.9 (3.3)	58.3 (8.2)	5.0 (1.5)	30.1 (9.0)	0.05 (0.05)	0.4 (0.3)	35.3 (14.8)	114.1 (47.9)	2.4	3.2	66.7	206.1
Bole only to 5-cm top	13.3 (1.2)	47.1 (4.2)	4.9 (1.7)	29.5 (10.0)	0 (0)	0 (0)	38.5 (18.1)	130.6 (6.14)	2.4	3.2	59.1	210.4
Total tree	5.2 (1.1)	16.4 (3.6)	4.3 (2.4)	25.9 (14.8)	.3 (0.3)	2.4 (2.3)	14.1 (4.8)	48.7 (16.5)	2.4	3.2	26.3	96.6
Total tree plus	.9 (.4)	3.6 (1.7)	.2 (.1)	.6 (.2)	.1 (.1)	.9 (.9)	0 (0)	0 (0)	2.4	3.2	3.6	8.3

Values are means with one standard error in parentheses (n = 4 plots).

[a] Excluding old-growth stumps and snags.

Table 27—Description of forest floor classes used in the postharvest assessment at Fall River

Class	Name	Description
1	Intact forest floor	Undisturbed mat of brown and gray needles
2	Small slash or buried wood	Slash <0.6 cm in diameter or buried wood under the forest floor
3	Forest floor mixed with soil	Soil particles scattered on top of and among needles
4	Red rot	Decay class 5 material; reddish, unconsolidated woody pieces, found mostly in piles
5	Bare soil	Bare mineral soil

Table 28—Forest floor cover[a] and depth to mineral soil by forest floor condition and biomass-removal treatment at Fall River

Treatment	Intact forest floor		Small slash or buried wood		Forest floor mixed with soil		Red rot		Bare soil cover
	Cover	Depth	Cover	Depth	Cover	Depth	Cover	Depth	
	percent	*m*	*percent*	*cm*	*percent*	*cm*	*percent*	*cm*	*percent*
Bole only	66 (8.2)	8.8 (3.2)	51 (5.5)	14.5 (1.5)	9 (3.4)	11.1 (4.4)	18 (3.1)	19.0 (3.1)	4 (1.2)
Bole only to 5-cm top	59 (7.3)	10.4 (1.1)	47 (4.7)	11.1 (.8)	23 (6.7)	4.6 (3.0)	17 (3.0)	22.1 (5.2)	2 (.6)
Total tree	53 (3.5)	4.7 (1.0)	6 (2.6)	7.5 (.9)	16 (2.0)	1.6 (.5)	19 (3.3)	7.2 (.5)	6 (2.3)
Total tree plus	42 (4.5)	4.0 (1.0)	3 (2.8)	1.2 (1.2)	23 (3.3)	2.0 (.5)	24 (1.7)	7.0 (.7)	8 (1.7)

Values are means with one standard error in parentheses (n = 4 plots).

[a] Percentage of cover sums for a given treatment are greater than 100 because material from some classes overlapped in areas where buried wood was found.

We categorized five forest floor conditions based on visual observations (table 27). Intact forest floor with no slash ranged from 23 percent of the plot area in BO5 to 53 percent of the plot area in TT. Because woody debris obstructed the view of the forest floor in BO and BO5 treatments, we also examined underneath the woody debris and estimated an additional 37 percent of the plot area in these treatments contained intact forest floor. Thus, intact forest floor in BO and BO5 covered 66 and 59 percent of the plot areas (table 28). Areas with small slash and buried wood were more abundant in BO and BO5, covering 51 percent and 47 percent of the plot areas, respectively. Forest floor mixed with soil was least abundant in BO (9 percent) and most abundant in BO5 and TT+ (23 percent).

Red rot cover varied relatively little across treatments from 17 percent in BO5 to 24 percent in TT+ (table 28). Bare soil was relatively rare, but most frequent in the TT and TT+ treatments (6 percent and 8 percent, respectively), where large biomass amounts were removed.

Depth of the forest floor differed with treatment and category. Intact forest floor, small slash or buried wood, and red rot were two to three times as deep in

Table 29—Carbon (C) and nitrogen (N) concentrations in forest floor, small slash or buried wood, mixed forest floor, and red rot after forest harvesting at Fall River[a]

	Bole only		Bole only to 5-cm top		Total tree		Total tree plus	
Material	C	N	C	N	C	N	C	N
	Percent							
Intact forest floor	42.7	0.66	40.3	0.66	36.2	0.66	34.7	0.66
Small slash or buried wood	46.1	.58	46.1	.58	---	---	---	---
Forest floor mixed with soil	28.4	.55	28.4	.55	28.4	.55	28.4	.55
Red rot	48.8	.36	48.8	.36	48.8	.36	48.8	.36

[a] Mean values averaged across treatments were used when values were similar or statistical tests indicated that treatment differences were not significant.

BO and BO5 treatments as in TT and TT+ (table 28). Depths in BO and BO5 treatments were relatively similar to each other, as were depths in the TT and TT+ treatments. Depth of forest floor mixed with soil tended to be greater in BO (11 cm) compared to the other treatments. Red rot was scattered more in the TT and TT+ treatments because of dragging whole trees across the soil surface during cable yarding. In contrast, protective limbs and tops were left on the soil surface in the BO and BO5 treatments. Although a shovel-excavator working in the treatment buffers around measurement plots was used to either remove slash and CWD or uniformly scatter slash in all treatments, this equipment caused more scattering of red rot in treatments that had the most CWD removals. Considerable scattering and some inadvertent removal of red rot occurred in the buffer area of the TT treatment where the shovel excavator moved piles of broken tops and other logging slash out of the plot.

Carbon and N concentrations in intact forest floor, small slash, mixed forest floor, and red rot differed substantially (i.e., 28 to 49 percent for C, and 0.36 to 0.66 percent for N) (table 29). Red rot was the greatest mass among all forest floor materials within the BO and BO5 treatment, whereas intact forest floor was the greatest mass in TT and TT+ (table 30). The range in red rot biomass was from 20 Mg/ha in the TT treatment to 51 Mg/ha in the BO5 treatment. The unexpected low mass of red rot in the TT treatment compared to the BO and BO5 treatments may have been caused by the shovel excavator picking up, temporarily piling, and then removing broken limb material. Some red rot material could have been removed during this operation, as the buffer area represents 60 percent of the overall treatment plot. Another possibility is that there may have been initially small amounts

Table 30—Forest floor mass by forest floor condition and biomass-removal treatments at Fall River

Treatment	Intact forest floor	Small or buried slash	Forest floor mixed with soil	Red rot material	Total
			Mg/ha		
Bole only	29.8 (11.2)	20.2 (9.7)	0.7 (0.4)	46.9 (12.7)	97.6
Bole only to 5-cm top	33.1 (9.3)	16.3 (3.5)	2.0 (1.2)	51.1 (9.5)	102.5
Total tree	32.4 (2.9)	0 (0)	1.6 (1.0)	19.9 (4.5)	53.9
Total tree plus	29.9 (7.0)	0 (0)	4.8 (2.4)	23.9 (1.0)	58.6

Values are means with one standard error in parentheses (n = 4 plots per treatment).

of red rot on these plots, or that the sampling did not completely address the variability in this characteristic.

Intact forest floor mass was similar across all biomass removal treatments ranging from 30 to 33 Mg/ha (table 30). According to the tree biomass data, there should have been 10 Mg of fresh foliage added to the forest floor after the harvest in BO and BO5. Very little fresh foliage was left in TT and TT+ as fresh foliage was removed mechanically and by hand in these treatments. During future assessments, sampling intensity should be increased to detect differences in forest floor biomass between BO and BO5, and TT and TT+ treatments. Forest floor mass in the different treatments was also calculated by using forest floor cover percentage by class and depth, for each of mass and volume. Results from using this approach were similar to those for red rot material (table 30) (i.e., 6.1 percent greater values, on average, with the alternative approach), and small or buried slash (i.e., 8 percent greater on average). Differences between the two methods were extremely large (i.e., up to threefold) for forest floor mixed with soil probably because of broad variability in mass per unit volume recorded when sampling these classes. As a consequence, the method consisting of calculating mass of forest floor classes by collecting, drying, and determining weights per unit area was adopted as the more reliable calculation method.

Red rot was a significant store of C and N in the BO and BO5 treatments.

Small or buried slash ranged from 0 Mg/ha in TT treatments to 20 Mg/ha in BO. The 16 and 20 Mg/ha of buried slash in the BO and BO5 treatments, respectively, is a store that is often missed in postharvest forest floor sampling protocols. Mixed forest floor had the smallest mass among all treatments and ranged from 1 in BO to 5 Mg/ha in TT+.

Carbon and N stores in intact forest floor were similar for all treatments ranging from 10 to 13 Mg/ha for C and 197 to 218 kg/ha for N (table 31). As expected,

Table 31—Carbon (C) and nitrogen (N) stores in forest floor components at Fall River by treatment

Treatment	Intact forest floor		Small or buried slash		Forest floor mixed with soil		Red rot		Total	
	C	N	C	N	C	N	C	N	C	N
	Mg/ha	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*	*Mg/ha*	*kg/ha*
Bole only	12.7 (4.8)	196.7 (73.9)	9.3 (4.5)	117.2 (56.3)	0.2 (0.1)	3.9 (2.2)	22.9 (6.2)	168.8 (45.7)	45.1	486.6
Bole only to 5-cm top	13.3 (3.7)	218.5 (61.4)	7.5 (1.6)	94.5 (20.3)	.6 (.3)	11.0 (6.6)	24.9 (4.6)	184.0 (34.2)	46.3	508.0
Total tree	11.7 (1.0)	213.8 (19.1)	0 (0)	0 (0)	.5 (.3)	8.8 (5.5)	9.7 (2.2)	71.6 (16.2)	21.9	294.2
Total tree plus	10.4 (2.4)	197.3 (46.2)	0 (0)	0 (0)	1.4 (.7)	26.4 (13.2)	11.7 (.5)	86.0 (3.6)	23.5	309.7

Values are means with one standard error in parentheses (n = 4 plots per treatment).

Table 32—Summary of biomass and carbon and nitrogen stores after forest harvest at Fall River

	Biomass				Carbon				Nitrogen			
	BO	BO5	TT	TT+	BO	BO5	TT	TT+	BO	BO5	TT	TT+
	Mg/ha				*Mg/ha*				*kg/ha*			
Coarse woody debris[a]	60.0	37.3	20.0	2.4	29.0	18.2	9.8	1.2	88.8	76.6	44.7	5.1
Old-growth stumps/snags	34.9	28.8	29.7	47.2	17.6	14.7	14.9	23.2	28.9	29.0	23.5	35.4
Old-growth logs	70.0	76.3	27.9	0	35.3	38.5	14.1	0	114.1	130.6	48.7	0
Recent stumps	5.2				2.4				3.2			
Forest floor	97.6	102.5	53.9	58.6	45.1	46.3	21.9	23.5	486.6	508.0	294.2	309.7
Coarse roots	82.2				39.6				180.8			
Small/fine roots 0-45-cm depth	3.8				1.3				24.6			
Mineral soil 0-80 cm depth	458.7[b]				248.5				13 143.0			
Total	812.4	794.8	681.4	658.1	418.8	409.5	352.5	339.7	14 070.0	14 095.8	13 762.7	13 701.8

BO = bole-only removal, BO5 = bole-only to 5-cm top removal, TT = total-tree removal, TT+ = total-tree-plus removal.

[a] Excluding old-growth stumps, snags, logs, and recent stumps.

[b] Soil organic matter.

C and N stores in small and buried slash were quite similar for the BO and BO5 treatments (9 and 8 Mg/ha for C, and 117 and 94 kg/ha for N, respectively), and absent in the TT and TT+ treatments. Red rot was a significant store of C and N in BO and BO5 treatments (i.e., 23 and 25 Mg/ha for C, and 169 and 184 kg/ha for N, respectively).

Total N above the mineral soil averaged 734 kg/ha in BO and BO5, and decreased to 414 and 353 kg/ha in TT and TT+, respectively.

The postharvest assessment quantified biomass and C and N stores left in each treatment. Coarse woody debris, old-growth logs, and some forest floor components were the stores that changed substantially from pre- to postharvest time. After harvest, CWD biomass (excluding old-growth stumps, snags, and logs) ranged from 2 Mg/ha in TT+ to 60 Mg/ha in BO (table 32). Because of the harvest residues (i.e., branches, bole parts) left on the ground, biomass of CWD in BO was 2.7 times and in BO5 1.7 times the biomass in the preharvest assessment (table 23). Coarse woody debris was almost completely removed in TT+. Biomass of old-growth logs averaged 73 Mg/ha in BO and BO5, and 28 Mg/ha in TT. As planned, old-growth logs were completely removed in the TT+ treatment. Forest floor biomass was similar in BO compared to BO5 (98 vs. 102 Mg/ha), and in TT compared to TT+ (54 vs. 59 Mg/ha).

Carbon stores ranged from 29 Mg/ha in BO to 1 Mg/ha in TT+ for CWD, from 0 Mg/ha in TT+ to 38 Mg/ha in BO5 for old-growth logs, and from 22 Mg/ha in TT to 46 Mg/ha in BO5 for forest floor (table 32). After the harvest, 89 kg N/ha remained in CWD in BO, but this store decreased to only 5 kg N/ha in TT+. Similarly, there was still 131 kg N/ha in old-growth logs in BO5 but nothing left in TT+. Relative to initial stand conditions, the forest floor N store increased in BO and BO5 but decreased in TT and TT+. The average N store in the forest floor within BO and BO5, and TT and TT+ was 497 and 302 kg N/ha, respectively.

Discussion

Postharvest CWD biomass in BO and BO5 at Fall River was markedly greater than that in TT and TT+. Forest floor represented greater biomass and C and N stores than CWD. If recent stumps and remnant old-growth logs, stumps, and snags were included in CWD, then this aggregate woody material C store would be greater than the forest floor C, but this would not be the case for N because of the large forest floor N stock.

Amounts and dimensions of CWD and old-growth logs are usually smaller in managed than in unmanaged forests (Duvall and Grigal 1999, Krankina and Harmon 1995, Spies et al. 1988), because substantial amounts of wood are removed at shorter intervals. Also, micrometeorological conditions, size of material, and soil nutrient processes in old-growth forests differ from those in harvested areas affecting the amount and size of downed wood (Edmonds et al. 1986). Consequently, the 170 Mg/ha of aboveground woody debris biomass in BO (CWD, old-growth stumps/snags, old-growth logs, and recent stumps) at Fall River was markedly lower than the 456 Mg/ha biomass of debris > 0.6 cm in diameter in an old-growth forest in Olympic National Park (Agee and Huff 1987).

Given the very low N concentrations in wood, CWD generally constitutes a relatively small N store (Graham 1982 as cited in Harmon and Sexton 1995, Sollins et al. 1987). Its sheer mass, however, can make CWD a substantial C pool especially in those treatments that leave large amounts of residue on site as was the case for BO and BO5 at Fall River. Old-growth logs at Fall River originated both by natural death in the old-growth forest present before 1952-53, and from nonmerchantable portions of logs felled or bucked during harvesting of the old-growth stand. Large old-growth logs may persist for up to 200 years (Sollins et al. 1987). Old-growth log mass in Douglas-fir forests in western Oregon averaged 215 Mg/ha (Sollins et al. 1980), or about three times as much as the old-growth log residues in BO and BO5 at Fall River. In the future, logs greater than 60 cm will not be a common component in the woody debris store in intensively managed Douglas-fir stands except perhaps in some riparian-zone buffers.

Coarse woody debris plus old-growth logs, stumps, and snags constituted major C pools in BO, BO5, and TT, but represented a relatively minor N store compared with forest floor and, possibly, roots. Given their average C:N ratio of 296, old-growth logs likely contribute little to total N availability of the site, but they are important for long-term C storage. At 5.2 Mg/ha, recent stumps composed a small biomass store. Although stump removal has been linked to smaller root collar diameter and less total N content in 4-year-old Douglas-fir and western white pine in northern Idaho (Page-Dumroese et al. 1998), this could be alternatively attributed to displaced topsoil.

The amount of red rot, buried slash, and CWD in BO and BO5 was markedly greater than in TT and TT+. Harvest in BO and BO5 left slash and foliage from the felled trees, which were removed in TT and TT+. The proportion of bare soil increased in TT and TT+, and additional bare soil was created in TT+ because of the removal of all old-growth logs. The forest floor/red rot that existed before harvest was also scattered somewhat during the harvesting operation in TT and TT+ because no slash covered the soil surface when trees were cable-yarded out of the plots. In contrast, the woody residues in BO and BO5 plots protected the forest floor against mechanical dispersion.

The forest floor pool was the largest C pool above the mineral soil in all biomass removal treatments. Greater C concentration in red rot than in intact forest floor resulted in red rot being the largest C store among forest floor components in BO, BO5, and TT+. The intact forest floor, however, was the largest N store among forest floor components across all treatments. The intact forest floor is likely to most rapidly decompose, mineralize, and quickly supply nutrients to the growing trees because of its relatively low C:N ratio (Edmonds 1979). Buried slash and fine roots will also likely decompose quickly because of warmer temperature near the surface soil.

On average, 18 Mg/ha of small or buried slash was found in BO and BO5. This material was removed in the TT and TT+ treatments, when mostly broken limbs were removed from plots. In addition, more logging slash may have been pushed into the soil surface during the logging operation in BO and BO5. The C:N ratio of this buried material at Fall River was 80 compared with 225 (49.4/0.22) in fresh class 1 to 2 limb material. Bole-only and BO5 contained far more of this material than TT and TT+, suggesting that short-term N-immobilization after imposing the treatments may be greater in BO and BO5 that in TT and TT+.

Biomass-removal treatments had a significantly greater impact on the site C store than the N store because of the large N reservoir in the mineral soil.

Biomass, C, and N Removals

Methods

Biomass removals were not measured directly during the harvest operation. Instead, we calculated removals in each biomass-removal treatment by subtracting the average sum of CWD and forest floor left after harvest in the treatment from the sum of the preharvest standing crop biomass in bole wood, bark, live and dead branches, foliage, dead trees and snags, CWD, and the forest floor prior to harvest. Preharvest estimates of these stores were based on plot averages for all 48 study plots. In addition, as we did not measure old-growth logs in the TT+ at plot-level accuracy prior to harvest, we estimated the old-growth log removals in this treatment by using the average postharvest estimate present in the BO, BO5, and TT treatments, because we believe that Brown's transect method, used only in the postharvest assessment, provided the best estimate of this component. Carbon and N removals in the different treatments were calculated by multiplying biomass removal levels in each component by elemental concentrations for that component.

Results

Estimated biomass removed during harvest averaged 358 Mg/ha in BO, 381 Mg/ha in BO5, 424 Mg/ha in TT, and 498 Mg/ha in TT+ (fig. 15). These removals represent

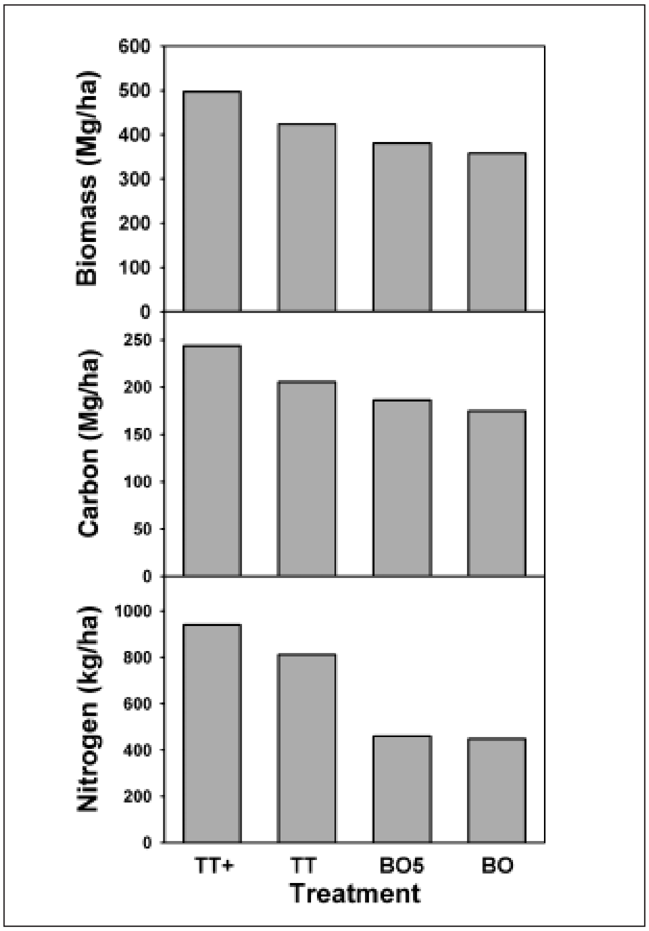

Figure 15—Biomass, carbon, and nitrogen removals at harvest at the Fall River research area. Treatments are bole-only removal (BO), bole to 5-cm top removal (BO5), total-tree removal (TT), and total-tree plus all-legacy-wood removal (TT+).

59 to 82 percent of the initial biomass store above the mineral soil, and 31 to 43 percent of the initial biomass store (including soil organic matter) to 80-cm soil depth. Estimated C removals were 175 Mg/ha in BO, 187 Mg/ha in BO5, 206 Mg/ha in TT, and 244 Mg/ha in TT+. Fractions of the initial C store removed were similar to those for biomass: 60 to 83 percent of the C store above the mineral soil, and 30 to 42 percent of the total C store to 80-cm soil depth. Estimated N amounts removed during harvest were 432 kg/ha in BO, 445 kg/ha in BO5, 796 kg/ha in TT, and 925 kg/ha in TT+. Compared with the biomass and C pools, greater proportions of the initial N store above the mineral soil were removed at harvest (33 to 70 percent), but the total N store to 80-cm soil depth only decreased by 3 to 6 percent because of the large belowground N stores.

Discussion

The treatment array at Fall River provided a wide range of biomass removals from 498 Mg/ha in TT+ to 358 Mg/ha in BO. Differences in biomass removals between BO and BO5 were small, as this change in the merchantable wood standard had a relatively minor impact on removals even though most wood greater than 5 cm in diameter was removed in BO5 regardless of length. Equipment operators inadvertently removed some CWD and forest floor as they piled and removed broken limbs and tops from TT plots. In an operational total-tree harvest operation, most limbs are broken off in the felling and forwarding operations, and considerable mass of broken tops, limbs, and branches would be left in place.

Absolute biomass removals at Fall River (498 Mg/ha in TT+) were within the upper third of the range recorded in the LTSP sites that encompassed 96 to 532 Mg/ha of removals (Powers et al. 2005). Relative biomass removals at Fall River mostly fell within the mid-third of the 42- to 100-percent range in the LTSP sites. The most intensive biomass removal treatment at Fall River (i.e., TT+), however, did not remove all forest floor as was done in the LTSP studies (Powers et al. 2005). Had the forest floor been removed, the removal would have increased to 559 Mg/ha, exceeding the range noted above.

Total site N was only reduced by 6 percent in the most intensive biomass-removal treatment (TT+).

Estimated N removals at Fall River (925 kg/ha in TT+) were mostly within the upper half of the LTSP site range of 98 to 1068 kg/ha (Powers et al. 2005). The fraction of N above the mineral soil removed at Fall River ranged from 33 to 70 percent and from 18 to 100 percent in the other LTSP site installation. If total forest floor removal at Fall River had been similar to other LTSP studies, it would have increased N removals to 1240 kg/ha.

A “stability ratio” (Evans 1999) has been proposed as an indicator of unstable or nonsustainable conditions created by excessive nutrient removals. The ratio is calculated as the proportion of a nutrient removed relative to the total site capital of the nutrient. A stability ratio greater than 0.3 (i.e., 30 percent of the nutrient store removed) likely indicates serious long-term stability concerns, and a stability ratio greater than 0.5 would create an immediate stability concern. The stability ratios for the biomass-removal treatments at Fall River were 0.03, 0.03, 0.04, and 0.06 for BO, BO5, TT, and TT+. Even if the forest floor had been removed, the stability ratio would have only been 0.08. These low removal ratios are a consequence of the high amount of N in the mineral soil at Fall River. Long-term tree-growth monitoring within the Fall River study will ultimately determine whether site productivity has been impacted by biomass removals at harvest. The assessment of the existing and removed biomass and C and N stores will be of value when tree growth and soil/tree physiological processes are evaluated across treatments and when study results are compared and contrasted with other studies.

Final Remarks

Lessons Learned

One of the primary objectives of the Fall River study was to add to the strategic forest productivity database in the Pacific Northwest and enhance understanding of the consequences of biomass manipulation, ground-based harvesting, and vegetation control for short- and long-term forest productivity. Through affiliation with the USFS LTSP network, much can be learned by comparing treatment responses across a wide range of sites. Also, active interaction with the participants in that research program improved the experimental design and methodological approaches used at Fall River. The national study benefits from the research at Fall River by adding data from a study with (1) high site quality, (2) additional treatments, (3) additional assessments and protocols, and (4) replicated treatments.

Research at Fall River is designed to contribute to the understanding of mechanisms of treatment response and to better define soil quality thresholds (i.e., soil property values that are advantageous, inconsequential, or detrimental to tree growth) and to improve guidelines for best management practices. Characterizing pre- and postharvest biomass and nutrient stocks is a critical step in long-term site productivity studies, and permits interpretation of how base-level conditions were altered by the imposed conditions, particularly biomass manipulation treatments. We believe that the postharvest treatment assessments are especially important because unintended operations during treatment implementation can affect treatment outcomes. At Fall River, for example, we confirmed that some forest floor removal did occur in the total-tree removal treatments when the shovel-excavator removed small limbs and broken tops.

The Fall River study was designed to include biomass-removal, soil-compaction, and vegetation-control treatments similar to those of the LTSP program. The soil-compaction treatment achieved by ground-based harvesting of commercial boles provided realistic treatment conditions that will allow information to be directly transferred to operational guidelines for similar sites. After imposing the biomass-removal treatments, we realized that BO and BO5 were similar in terms of the amount of the material removed from the site. In retrospect, we believe that it may have been better to replace BO5 either with a mini-piling treatment, which is used operationally for heavy slash conditions to provide more favorable planting spots, or with a total CWD plus forest floor removal treatment like that in other

LTSP study sites. Testing the mini-pile treatment would have enabled us to evaluate effects and operational value of manipulating biomass without removing it from the site. The mini-piling treatment at Fall River was dropped because the study plot size was deemed too small to accommodate the treatment. In hindsight, however, we believe this treatment could have been installed successfully. The mini-piling treatment is being tested in LTSP studies recently installed in the Olympic Peninsula (Washington) and in the Western Cascades (Oregon) (Harrington et al. 2005). Testing the full forest floor removal treatment would have also provided a wider range of biomass-removal treatments. Having one treatment beyond normal operational treatments is beneficial because it allows interpolation between treatment values rather than extrapolation of results. In addition, extreme treatments help to better understand the resiliency or susceptibility of the site to disturbance, and the potential for ameliorative treatments to restore productivity potential.

Local biomass equations for Douglas-fir and western hemlock generated from trees felled at the harvested stand at Fall River were important to more accurately estimate component biomass, and biomass and nutrient removal. The widely used equations by Gholz et al. (1979) developed for larger trees overestimated some components of biomass, particularly foliage of Douglas-fir.

Two methods were used for assessing CWD: (1) a transect method whereby all CWD within 30-cm by 15-m transects were classified and weighed, and (2) the line-transect method (Brown 1974, Harmon and Sexton 1995). The line-transect method was by far the most efficient, and likely the most accurate of the two methods. The transect method required daily collection of material for moisture content adjustment, and the occurrence of large logs oriented down the full transect caused large variation in biomass estimates. Calculating the volume of the logs intercepted by the transect was also challenging although a method was developed to determine log volumes. We would recommend that the line-transect method be used in future evaluations of CWD at the research site.

Subsequent plans for evaluation of forest floor biomass should include more samples per plot than those used in this investigation in order to address the increased variability that followed treatment implementation. A preliminary sampling across all treatments is recommended to determine an adequate sample size.

Great care was taken during this investigation to assure that red rot was properly sampled down to the mineral soil. Red rot can be a significant component of the forest floor biomass on some sites and should be sampled any time the forest floor biomass is determined. It was beneficial to separate the forest floor into components (e.g., red rot, intact and decomposed foliage, buried slash, etc.) in the postharvest forest floor assessment to understand the relative proportion of the area in different substrate materials. After harvest, buried wood and slash constituted a significant biomass pool and, therefore, should not be overlooked during forest floor characterization because of its role in nutrient cycling dynamics.

Two representative portions of the preharvest stand were not harvested. This was a wise decision that allowed us to contrast soil solution chemistry, N leaching, and soil temperature across a wide range of treatments including an uncut stand. Maintaining nonharvested plots within the study design would not have been prudent, as damage from windthrow could have been severe, and microsites within plots in proximity to the uncut stands would have had shading and other impacts from the old stand.

Another very useful study design decision was to plant extra trees in each plot to be destructively sampled for biomass determinations and other needs. The number of extra trees was the same in each plot, and equal tree counts were maintained across all treatments even though biomass harvest and other investigations took place only in selected treatments.

Finally, developing a collaborative working relationship across organizations (USFS Pacific Northwest Research Station, University of Washington College of Forest Resources, and Weyerhaeuser Company) was extremely valuable as team members brought different insights and skills to meet the broad range of study objectives. Additionally, this collaboration has spawned other long-term site productivity studies that expand the regional strategic database, and ancillary collaborative projects that further explore the mechanisms of treatment response. Equally important, this study allowed several graduate students to gain a broad range of experience and make significant research contributions.

Future Research Action and Directions

The long-term site productivity study at Fall River was designed as a full-rotation-cycle experiment. Hopefully, treatments can be repeated (or modified as needed) and carried out through multiple rotations. Although much has been learned in the 6 years (at the time of this writing) since study installation, the real value in the study comes from long-term assessment and from integrating findings with other regional and national LTSP studies. Followup actions that may be of value to understanding the implications of biomass removal, soil compaction, and vegetation control on site productivity are outlined below.

- Assessment of CWD and forest floor in BO, TT, and TT+ with vegetation control and in the BO without vegetation control should be made every

10 years or at least at midrotation and before thinning to understand how these pools change with time.

- Changes in mineral soil C and N could be assessed periodically in BO with and without vegetation control and in the TT+ treatment. In retrospect, it would have been better to sample soils to specified depths rather than sampling the A horizon first and then at specified depths below the A horizon. It was somewhat subjective to estimate where the A horizon ended and the AB horizon started at the study site.
- Tree growth, foliar nutrient content, and leaf area should be assessed at least every 5 years. Leaf area could be assessed by measuring light interception, recording litter fall, or with LIDAR technology.
- Fertilization treatments are part of the study's experimental design. Foliar nutrient concentration and content of Douglas-fir should be assessed periodically across treatments to determine if nutrients are becoming limiting. If nutrient limitations do not occur, fertilization should not be carried out, allowing more replications of the biomass removal treatments. If growth differences become evident between the most intensive organic-matter-removal treatment and the other treatments, this may be an indicator that fertilization is needed.
- The stand planted at 1,600 trees/ha should be thinned when treatments reach a given relative density, so that early treatment differences are not subsequently negated by severe between-tree competition.
- There is considerable value in carrying this study through multiple rotations with similar treatments (and probably replacing the BO5 treatment with a total forest floor removal treatment). The next clearcut harvest at Fall River could occur earlier (e.g., at age 30 to 35) than in current operational rotations to accelerate the information cycle and increase the disturbance pressure on the system. Fertilization treatments should be maintained as part of the study design in case biomass-removal treatments negatively affect tree growth.

Tree growth, foliar nutrient content, and leaf area should be assessed at least every 5 years.

Additional research directions that could be explored are outlined below:

- Data arising from the Fall River and other LTSP studies could be used to validate the stability ratio concept (Evans 1999) and the proposition that long-term site productivity would decline if that ratio is greater than 0.3 (i.e., removal of more than 30 percent of a growth-limiting nutrient store). This is a simple approach that needs to be refined through a better understanding of tree nutrient demands and site supply dynamics across treatments and sites.

- Tree growth data by treatment at Fall River and other LTSP sites could be compared to growth potential predictions from physiological-based models (e.g., 3P-G, Waring and McDowell 2002) to determine how accurately they predict growth across the range of site and treatment conditions. Carbon sequestration, C contributions to the atmosphere, and C storage in deep soil layers could also be assessed.

Developing a regional strategic database aimed at maintaining and enhancing forest productivity, and understanding the implications of intensive management on tree growth will continue to be a worthwhile endeavor. Whatever the future brings, public agency, university, and forest industry collaboration on this research will likely be the most fruitful approach for gaining scientific knowledge. A study of this magnitude cannot be completed without the dedication and full support of each organization involved and other sponsors. Resources and commitment allowed project continuity, enabling us to assemble and summarize the pre- and postharvest site characterization and biomass and nutrient store data. We hope that this report will provide useful information for those interested in forest sustainability issues and for the scientists working on the study in the future.

Acknowledgments

We are grateful to Weyerhaeuser Company, the National Council for Air and Stream Improvement, and the USDA Forest Service Pacific Northwest Research Station for financial support for the study installation and various site characterization activities within the project. This is a product of the Sustainable Forestry component of Agenda 2020, a joint effort of the USDA Forest Service Research and Development and the American Forest and Paper Association. We thank Alex Dobkowski, Peter Farnum, Ron Heninger, and Bill Scott for their contributions to study design and in the site selection phase of the study. We also acknowledge Eric Beach, Teiko Breid, Karl Buermeyer, Paul Carpenter, Lance Christensen, Warren Devine, Chris Diaz, James Dollins, Christel Kern, Bridget Korman, Rick Leon, Diana Livada, Ryan Mansfield, David Marshall, Deborah Page-Dumroese, David Peter, Kyle Petersen, Robert Powers, Ed Seymore, Amy Sidell, Smythe and Prante Forestry, Douglas Waldren, Bryan Wender, and Darlene Zabowski for assistance at various stages of the project. We express our deep gratitude to Mary Beth Adams, James Boyle, Ron Heninger, Lana D’Souza, Robert Edmonds, and Peter Homann for reviewing the manuscript.

English Equivalents

When you know:	Multiply by:	To find:
Degrees Celsius (°C)	(°C x 1.8) + 32	Degrees Fahrenheit (°F)
Angstroms (Å)	3.94^{-9}	Inches (in)
Nanometer (nm)	3.94^{-8}	Inches (in)
Centimeters (cm)	0.394	Inches (in)
Meters (m)	3.281	Feet
Kilometers (km)	0.621	Miles
Square meters (m^2)	10.76	Square feet (ft^2)
Square meters per hectare (m^2/ha)	4.356	Square feet per acre (ft^2/ac)
Hectares (ha)	2.471	Acres (ac)
Kilograms (kg)	2.205	Pounds (lb)
Kilograms per hectare (kg/ha)	0.891	Pounds per acre (lb/ac)
Megagrams per hectare (Mg/ha)	0.446	Tons per acre (T/ac)
Megagrams per hectare	892	Pounds per acre (lb/ac)
Grams per cubic centimeter (g/cm^3)	0.036	Pounds per cubic inch (lb/in^3)
Cubic meters per square meter (m^3/m^2)	3.285	Cubic feet per square foot (ft^3/ft^2)
Liters per hectare (L/ha)	0.107	Gallons per acre
Trees per hectare	2.471	Trees per acre
Kilopascals (kPa)	0.145	Pounds per square inch (lb/in^2)
Megajoules per square meter (MJ/m^2)	68,517	Foot-pounds (force) per square foot
Megajoules per square meter	88.10	British Thermal Units per square foot

Literature Cited

Agee, J.K.; Huff, M.H. 1987. Fuel succession in western hemlock/Douglas-fir forest. Canadian Journal of Forest Research. 17: 697-704.

Ares, A.; Terry, T.A.; Miller, R.E.; Anderson, H.W.; Flaming, B.L. 2005. Forest harvest effects on soil physical properties and Douglas-fir growth. Soil Science Society of America Journal. 69: 1822-1832.

Aubry, K.B.; Hall, P.A. 1991. Terrestrial amphibian communities on the southern Washington Cascade Range. In: Ruggiero, L.F.; Aubry, K.B.; Carey, A.B.; Huff, M.H., tech. coords. Wildlife and vegetation of unmanaged Douglas-fir forests. Gen. Tech. Rep. PNW-GTR-285. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 327-338.

Bancalari, M.A.E.; Perry, D.A. 1987. Distribution and increment of biomass in adjacent young Douglas-fir stands with different early growth rates. Canadian Journal of Forest Research. 17: 722-730.

Barclay, H.J.; Pang, P.C.; Pollard, D.F.W. 1986. Aboveground biomass distribution within trees and stands in thinned and fertilized Douglas-fir. Canadian Journal of Forest Research. 16: 438-442.

Bhadoria, P.B.S. 1986. Transport of anions towards root as influenced by soil compaction. Plant and Soil. 208: 9-19.

Bigger, C.M. 1988. Effects of harvest intensity on nutrient removal, nutrient leaching and growth of seedlings in individual stands of high and low productivity red alder and Douglas-fir. Seattle, WA: University of Washington. 178 p. Ph.D. dissertation.

Blumfield, T.J.; Xu, Z.H. 2003. Impact of harvest residues on soil mineral nitrogen dynamics following clearfall harvesting of a hoop pine plantation in subtropical Australia. Forest Ecology and Management. 179: 55-67.

Bonham, C.D. 1989. Measurements for terrestrial vegetation. New York: Wiley. 338 p.

Boyle, J.R. 1976. A system for evaluating potential impacts of whole-tree harvesting on site quality. Tappi. 59: 79-81

Brais, S. 2001. Persistence of soil compaction and effects on seedling growth in northwestern Quebec. Soil Science Society of America Journal. 65: 1263-1271.

Briggs, D.G. 1994. Forest products measurements and conversion factors—with special reference to the U.S. Pacific Northwest. Institute of Forest Resources Contribution 75. Seattle, WA: College of Forest Resources, University of Washington. 161 p.

Brown, J.K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. GTR-INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Bruce, D.; DeMars, D.J. 1974. Volume equations for second-growth Douglas-fir. Res. Note PNW-RN-239. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 5 p.

Bull, E.L.; Heater, T.W. 2000. Resting and denning sites of American martens in northeastern Oregon. Northwest Science. 74: 179-185.

Bull, E.L.; Holthaunsen, R.S.; Henjum, M.G. 1992. Roost trees used by pileated woodpeckers in northeastern Oregon. Journal of Wildlife Management. 56: 786-793.

Carey, A.B.; Johnson, M.L. 1995. Small mammals in managed, naturally young, and old-growth forests. Ecological Applications. 5: 336-352.

Carlyle, J.C.; Bligh, M.W.; Nambiar, E.K.S. 1998. Woody residue management to reduce nitrogen and phosphorus leaching from sandy soil after clear-felling *Pinus radiata* plantations. Canadian Journal of Forest Research. 28: 1222-1232.

Christiansen, R.L.; Yeats, R.S. 1992. Post-Laramide geology of the U.S. Cordilleran region. In: Burchfiel, B.C.; Lipman, P.W.; Zoback, M.L., eds. The Cordilleran Orogen: conterminous U.S.: the geology of North America. Decade of North American Geology. Boulder, CO: Geological Society of America: 261-406. Vol. G-3.

Cole, D.W.; Gessel, S.P. 1965. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. In: Youngberg, C.T., ed. Forest-soil relationships in North America. Proceedings, North American forest soils conference. Corvallis, OR: Oregon State University Press: 95-104.

Compton, J.E.; Cole, D.W. 1990. Impact of harvest intensity on growth and nutrition of second rotation Douglas-fir. In: Dyck, W.J.; Mees, C.A., eds. Proceedings, International Energy Agency/International Biological Program workshop on long-term field trials to assess environmental impacts of harvesting. FRI Bull. 161. Rotorua, New Zealand: New Zealand Forest Research Institute: 151-162.

Conlin, T.S.S.; van den Driessche, R. 1996. Short-term effects of soil compaction on growth of *Pinus contorta* seedlings. Canadian Journal of Forest Research. 26: 727-739.

Daly, C.; Neilson, R.P.; Phillips, D.L. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology. 33: 140-158.

Dice, S.F. 1970. The biomass and nutrient flux in a second growth Douglas-fir ecosystem. Seattle, WA: University of Washington. 165 p. Ph.D. dissertation.

Dick, R.P.; Myrold, D.D.; Kerle, E.A. 1988. Microbial biomass and soil enzyme activities in compacted and rehabilitated skid trail soils. Soil Science Society of America Journal. 52: 512-516.

Dimock, E.J., II; Beebe, T.F.; Collard, E.B. 1983. Planting-site preparation with herbicides to aid conifer reforestation. Weed Science. 31: 215-221.

Duvall, M.D.; Grigal, D.F. 1999. Effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes States, U.S.A. Canadian Journal of Forest Research. 29: 1926-1934.

Edmonds, R.L. 1979. Decomposition and nutrient release in Douglas-fir needle litter in relation to stand development. Canadian Journal of Forest Research. 9: 132-140.

Edmonds, R.L. 1991. Organic decomposition in Western United States forests. In: Harvey, A.E.; Neuenschwander, L.F., eds. Proceedings, Symposium on management and productivity of western montane forest soils. Gen. Tech. Rep. INT-280. Odgen, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 118-128.

Edmonds, R.L.; Binkley, D.; Feller, M.C.; Sollins, P.; Abee, A.; Myrold, D.D. 1989. Nutrient cycling: effects on productivity of Northwest forests. In: Perry, D.A.; Meurisse, R.; Thomas, B.; Miller, R.; Means, J.; Sollins, R.; Cromack, K., Jr.; Boyle, J.R., eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press: 17-35.

Edmonds, R.L.; Chappell, H.N. 1993. Relationship between soil organic matter and forest productivity in western Oregon and Washington. Canadian Journal of Forest Research. 24: 1101-1106.

Edmonds, R.L.; Eglitis, A. 1989. The role of the Douglas-fir beetle and wood borers in the decomposition of and nutrient release from Douglas-fir logs. Canadian Journal of Forest Research. 19: 853-859.

Edmonds, R.L.; Vogt, D.J.; Sandberg, D.H.; Driver, C.H. 1986. Decomposition of Douglas-fir and red alder wood in clear-cuttings. Forests. 13: 469-487.

Egnell, G.; Valinger, E. 2003. Survival, growth, and growth allocation of planted Scots pine trees after different levels of biomass removal in clear-felling. Forest Ecology and Management. 177: 65-74.

Eissenstat, D.M.; Mitchell, J.E. 1983. Effects of seeding grass and clover on growth and water potential of Douglas-fir seedlings. Forest Science. 29: 166-179.

Elliott, K.J.; White, A.S. 1987. Competitive effects of various grasses and forbs on ponderosa pine seedlings. Forest Science. 33: 356-366.

Evans, J. 1999. Sustainability of forest plantations: the evidence—a review of evidence concerning narrow-sense sustainability of planted forests. London, United Kingdom: Department for International Development. 64 p.

Fenn, M.E.; Poth, M.A.; Aber, J.D.; Baron, J.S.; Bormann, B.T.; Johnson, D.W.; Lemly, A.D.; McNulty, S.G.; Ryan, D.F.; Stottlemeyer, R. 1998. Nitrogen excess in North American ecosystems: predisposing factors, ecosystem responses, and management strategies. Ecological Applications. 8: 706-733.

Flint, L.E.; Childs, S.W. 1987. Effect of shading, mulching and vegetation control on Douglas-fir seedling growth and soil water supply. Forest Ecology and Management. 18: 189-203.

Franklin, J.F. 1990. Old-growth forests and the New Forestry. In: Pearson, A.F.; Challenger, D.A., eds. Wild and managed: differences and consequences. Vancouver, BC: University of British Columbia, Vancouver: 1-20.

Franklin, J.F.; Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 417 p.

Freedman, B.; Morash, R.; Hanson, A.J. 1981. Biomass and nutrient removals by conventional and whole-tree clearcutting of red spruce-balsam fir stand in central Nova Scotia. Canadian Journal of Forest Research. 11: 249-257.

Froehlich, H.A.; Miles, D.W.R.; Robbins, R.W. 1986. Growth of young *Pinus ponderosa* and *Pinus contorta* on compacted soil in central Washington. Forest Ecology and Management. 15: 285-294.

Fujimori, T.; Kawanabe, S.; Saito, H.; Grier, C.C.; Shidei, T. 1976. Biomass and primary production in forests of three major vegetation zones of the Northwestern United States. Journal of the Japanese Forestry Society. 58: 360-373.

Gessel, S.P.; Miller, R.E.; Cole, D.W. 1990. Relative importance of water and nutrients on the growth of coast Douglas-fir in the Pacific Northwest. Forest Ecology and Management. 30: 327-340.

Gholz, H.L.; Grier, C.C.; Campbell, A.G.; Brown, A.T. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Res. Pap. 41. Corvallis, OR: Forest Research Laboratory, Oregon State University. 39 p.

Gomez, A.; Powers, R.F.; Singer, M.J.; Horwath, W.R. 2002a. N uptake and N status in ponderosa pine as affected by soil compaction and forest floor removal. Plant and Soil. 242: 263-275.

Gomez, A.; Powers, R.F.; Singer, M.J.; Horwath, W.R. 2002b. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Science Society of America Journal. 66: 1334-1343.

Graham, R.L. 1982. Biomass dynamics of dead Douglas-fir and western hemlock boles in mid-elevation forests of Cascade Range. Corvallis, OR: Oregon State University. 152 p. Ph.D. dissertation.

Greacen, E.L.; Sands, R. 1980. Compaction of forest soils: a review. Australian Journal of Soil Research. 18: 163-189.

Grier, C.C.; Logan, R.S. 1977. Old-growth *Pseudotsuga menziesii* communities of a western Oregon watershed: biomass distribution and production budgets. Ecological Monographs. 47: 373-400.

Harmon, M.E.; Bible, K.; Shaw, D.; Remillard, S.; Sexton, J.; Fasth, B.; Priestley, A.; Chen, J.; Franklin, J.F. 1998. Permanent plots surrounding the Wind River Canopy Crane. Pacific Northwest Rep. 1. Corvallis, OR: H.J. Andrews Experimental Long-Term Ecological Research Site. http:/www/fsl.orst.edu/lter. (9 November 2005).

Harmon, M.E.; Franklin, J.F.; Swanson, F.J.; Sollins, P.; Gregory, S.V. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research. 15: 133-302.

Harmon, M.E.; Hua, C. 1991. Coarse woody debris dynamics in two old-growth ecosystems: comparing a deciduous forest in China and a conifer forest in Oregon. BioScience. 41: 604-610.

Harmon, M.E.; Marks, B. 2002. Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. Canadian Journal of Forest Research. 32: 863-877.

Harmon, M.E.; Sexton, J. 1995. Water balance of conifer logs in early stages of decomposition. Plant and Soil. 172: 141-152.

Harmon, M.E.; Sexton, J. 1996. Guidelines for measurements of woody detritus in forest ecosystems. Publication 20. Seattle, WA: University of Washington, U.S. LTER Network Office. 73 p.

Harmon, M.E.; Sexton, J.; Caldwell, B.A.; Carpenter, S.E. 1994. Fungal sporocarp mediated losses of Ca, Fe, K, Mg, Mn, N, P, and Zn from conifer logs in the early states of decomposition. Canadian Journal of Forest Research. 24: 1883-1893.

Harrington, T.B.; Harrington, C.A.; Schoenholtz, S.H. 2005. Forest productivity responses to logging debris and competing vegetation: effects of annual precipitation and soil texture. In: Harrington, C.A.; Schoenholtz, S.H., eds. Productivity of Western forests: a forest products focus. Gen. Tech. Rep. PNW-GTR-642. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 173-175.

Hatchell, G.E.; Ralston, C.W.; Foil, R.R. 1970. Soil disturbances in logging: effects on soil characteristics and growth of loblolly pine in the Atlantic Coastal Plain. Journal of Forestry. 68: 772-775.

Heilman, P.E. 1961. Effects of nitrogen fertilizer on the growth and nitrogen nutrition of low-site Douglas-fir stands. Seattle, WA: University of Washington. 214 p. Ph.D. dissertation.

Henderson, J.A.; Peter, D.H.; Lesher, R.D.; Shaw, D.C. 1989. Forested plant associations of the Olympic National Forest. Tech. Pap. R6-ECOL-TP 001-88. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 502 p.

Heninger, R.L.; Terry, T.A.; Dobkowski, A.; Scott, W. 1997. Managing for site productivity: Weyerhaeuser’s forestry perspective. Biomass and Bioenergy. 13: 255-267.

Herbauts, J.; El Bayad, J.; Gruber, W. 1996. Influence of logging traffic on the hydromorphic degradation of acid forest soils developed on lessic loam in middle Belgium. Forest Ecology and Management. 87: 193-207.

Homann, P.S.; Caldwell, B.A.; Chappell, H.N.; Sollins, P.; Swanston, C.W. 2001. Douglas-fir soil C and N properties a decade after termination of urea fertilization. Canadian Journal of Forest Research. 31: 2225-2236.

Jones, H.E.; Madeira, M.; Herraez, L.; Dighton, J.; Fabiâo, A.; González-Rio, F.; Marcos, M.F.; Gomez, C.; Tomé, M.; Feith, H.; Magalháes, M.C.; Howson, G. 1999. The effect of organic-matter management on the productivity of *Eucalyptus globulus* stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. Forest Ecology and Management. 122: 73-86.

Jurgensen, M.F.; Graham, R.T.; Larsen, M.J.; Harvey, A.E. 1992. Clear-cutting, woody residue removal, and nonsymbiotic nitrogen fixation in forest soils of the inland Pacific Northwest. Canadian Journal of Forest Research. 22: 1172-1178.

Kalra, Y.P.; Maynard, D.G. 1991. Methods manual for forest soil and plant analysis. Info. Rep. NOR-X-319. Edmonton, AB: Forestry Canada, Northwest Region, Northern Forestry Center. 116 p.

Keenan, R.J.; Prescott, C.E.; Kimmins, P.J. 1993. Mass and nutrient content of woody debris and forest floor in western red cedar and western hemlock forests on northern Vancouver Island. Canadian Journal of Forest Research. 23: 1052-1059.

Keyes, M.R.; Grier, C.C. 1981. Above- and below-ground net production in 40-year-old Douglas-fir stands on low and high productive sites. Canadian Journal of Forest Research. 11: 599-605.

King, J. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Paper 8. Centralia, WA: Weyerhaeuser Company, Forestry Research Center. 49 p.

Klopatek, J.M. 2002. Belowground carbon pools and processes in different age stands of Douglas-fir. Tree Physiology. 22: 197-204.

Krankina, O.N.; Harmon, M.E. 1995. Dynamics of the dead wood carbon pool in northwestern Russian boreal forests. Water, Air, and Soil Pollution. 82: 227-238.

Laiho, R.; Prescott, C.E. 2004. Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis. Canadian Journal of Forest Research. 34: 763-777.

Lasmanis, R. 1991. The geology of Washington. Rocks and Minerals. 66: 262-277.

Lenhard, R.J. 1986. Changes in void distribution and volume during compaction of a forest soil. Soil Science Society of America Journal. 50: 462-464.

Ludovici, K.H.; Morris, L.A. 1997. Competition-induced reductions in soil water availability reduced pine root extension rates. Soil Science Society of America Journal. 61: 1196-1202.

Lugo, A.E.; Brown, S.C.; Dodson, R.; Smithland, T.S.; Shugart, H.H. 1999. The Holdridge life zones of the conterminous United States in relation to ecosystem monitoring. Journal of Biogeography. 26: 1025-1038.

Mann, L.K.; Johnson, D.W.; West, D.C.; Cole, D.W.; Hornbeck, J.W.; Martin, C.W.; Rickerk, H. 1988. Effect of whole-tree and stem-only clearcutting on post-harvest hydrologic losses, nutrient capital and regrowth. Forest Science. 34: 412-428.

Maser, C.; Anderson, R.G.; Cromack, K., Jr.; Williams, J.T.; Martin, R.E. 1979. Dead and down woody material. In: Thomas, J.W., ed. Wildlife habitats in managed forests in the Blue Mountains of Washington and Oregon. Agric. Handb. 553. Washington, DC: U.S. Department of Agriculture, Forest Service; Wildlife Management Institute; U.S. Department of the Interior, Bureau of Land Management: 79-95.

Maser, C.; Tarrant, R.F.; Trappe, J.M.; Franklin, J.F. 1988. From the forest to the sea: a story of fallen trees. Gen. Tech. Rep. PNW-GTR-229. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 153 p.

McDowell, N.G.; Balster, N.J.; Marshall, J.D. 2001. Belowground carbon allocation of Rocky Mountain Douglas-fir. Canadian Journal of Forest Research. 31: 1425-1436.

McRoberts, R.E.; McWilliams, W.H.; Reams, G.A.; Schmidt, T.L.; Jenkins, J.C.; O’Neil, K.P.; Miles, P.D.; Brand, G.J. 2004. Assessing sustainability using data from the Forest Inventory and Analysis Program of the United States Forest Service. Journal of Sustainable Forestry. 18: 23-46.

Means, J.E.; MacMillan, P.C.; Cromack, K., Jr. 1992. Biomass and nutrient content of Douglas-fir logs and other detrital pools in an old-growth forest, Oregon, U.S.A. Canadian Journal of Forest Research. 22: 1536-1546.

Mendham, D.S.; O’Connell, A.M.; Grove, T.S.; Rance, S.J. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management. 181: 357-372.

Miller, R.E.; Colbert, S.R.; Morris, L.A. 2004. Effects of heavy equipment on physical properties of soils and on long-term productivity: a review of literature and current research. Tech. Bull. 887. Research Triangle Park, NC: National Council for Air and Stream Improvement. 76 p.

Miller, R.E.; Obermeyer, E.L. 1996. Initial and continued effects of a release spray in a coastal Oregon Douglas-fir plantation. Res. Pap. PNW-RP-487. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 11 p.

Montreal Process. 1995. Criteria and indicators for the conservation and sustainable management of temporal and boreal forests. Catalogue Fo42-238/1995E. Hull, PQ: Canadian Forest Service.

Morris, L.A.; Moss, S.A.; Garbett, W.S. 1993. Competitive interference between selected herbaceous and woody plants and *Pinus taeda* L. during two growing seasons following planting. Forest Science. 39: 166-187.

Murphy, G.E. 1983. *Pinus radiata* survival, growth and form 4 years after planting off and on skidtrails. New Zealand Journal of Forestry. 28: 184-193.

Neary, D.G.; Morris, L.A.; Swindel, B.F. 1984. Site preparation and nutrient management in southern pine forests. In: Stone, E.L., ed. Forest soils and treatment impacts. Proceedings, 6th North American forest soils conference. Knoxville, TN: University of Tennessee: 121-144.

Neitro, W.A.; Binkley, V.W.; Cline, S.P.; Mannan, R.W.; Marcot, B.G.; Taylor, D.; Wagner, F.F. 1985. Snags (wildlife trees). In: Brown, E.R., ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. Publ. R6-F&WL-192. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region: 129-169.

Newton, M.; Preest, D.S. 1988. Growth and water relations of Douglas-fir (*Pseudotsuga menziesii*) seedlings under different weed control regimes. Weed Science. 36: 653-662.

O'Connell, A.M.; Grove, T.S.; Mendham, D.S.; Rance, S.J. 2004. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in southwestern Australia. Soil Biology and Biochemistry. 36: 39-48.

Page-Dumroese, D.S.; Harvey, A.E.; Jurgensen, M.F.; Amaranthus, M.P. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Canadian Journal of Forest Research. 78: 29-34.

Powers, R.F. 1989. Maintaining long-term forest productivity in the Pacific Northwest: defining the issues. In: Perry, D.A.; Meurisse, R.; Thomas, B.; Miller, R.; Means, J.; Sollins, R.; Cromack, K., Jr.; Boyle, J.R., eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press: 3-16.

Powers, R.F. 1999. On the sustainable productivity of planted forests. New Forests. 17: 263-306.

Powers, R.F. 2002. Effects of soil disturbance on the fundamental, sustainable productivity of managed forests. In: Verner, J., ed. Proceedings of a symposium on the Kings River Sustainable Forest Ecosystems Project: progress and current status. Gen. Tech. Rep. PSW-GTR-183. Davis, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 63-82.

Powers, R.F.; Fiddler, G.O. 1997. The North American long-term soil productivity study: progress through the first five years. Proceedings, 18th annual forest vegetation management conference. Sacramento, CA: U.S. Department of Agriculture, Forest Service: 88-102.

Powers, R.F.; Reynolds, P.E. 1999. Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient. Canadian Journal of Forest Research. 29: 1027-1038.

Powers, R.F.; Scott, D.A.; Sanchez, F.G.; Voldseth, R.A.; Page-Dumroese, D.; Elioff, J.D. 2005. The North American Long Term Soil Productivity Experiment. Findings from the first decade of research. Forest Ecology and Management. 220: 31-50.

Powers, R.F.; Tiarks, A.E.; Boyle, J.R. 1998. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. In: Adams, M.B.; Ramakrishna, K.; Davidson, E.A., eds. The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management. Spec. Publ. 53. Madison, WI: Soil Science Society of America: 53-80.

Proe, M.F.; Dutch, J. 1994. Impact of whole-tree harvesting on second-rotation growth of Sitka spruce: the first 10 years. Forest Ecology and Management. 66: 39-54.

Redlin, M.J. 1988. Comparison of regression models for biomass estimation of young Douglas-fir in western Washington. Seattle, WA: University of Washington. 168 p. M.S. thesis.

Roberts, S.D.; Harrington, C.A.; Terry, T.A. 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability and Douglas-fir seedling growth. Forest Ecology and Management. 205: 333-350.

Sands, R.; Greacen, E.L.; Gerard, G.J. 1979. Compaction of sandy soils in radiata pine forests. I. A penetrometer study. Australian Journal of Soil Research. 17: 101-113.

Santantonio, D.; Hermann, R.K.; Overton, W.S. 1977. Root biomass studies in forest ecosystems. Pedobiologia. 17: 1-31.

SAS Institute. 1999. SAS user's guide: statistics. Version 8. Cary, NC: SAS Institute.

Silkworth, D.R.; Grigal, D.F. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen *Populus tremuloides*. Soil Science Society of America Journal. 46: 626-631.

Silvester, W.B.; Sollins, P.; Verhoeven, T.; Cline, S.P. 1982. Nitrogen fixation and acetylene reduction in decaying conifer boles: effects of incubation time, aeration, and moisture content. Canadian Journal of Forest Research. 12: 646-652.

Smeltzer, D.L.K.; Bergdahl, D.R.; Donnelly, J.R. 1986. Forest ecosystem responses to artificially induced soil compaction. II. Selected soil microorganism populations. Canadian Journal of Forest Research. 16: 870-872.

Smethurst, P.J.; Nambiar, E.K.S. 1990. Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. Canadian Journal of Forest Research. 20: 1498-1507.

Smethurst, P.J.; Nambiar, E.K.S. 1995. Changes in soil carbon and nitrogen during the establishment of a second crop of *Pinus radiata*. Forest Ecology and Management. 73: 145-155.

Smith, C.W. 2003. Does soil compaction on harvesting extraction roads affect long-term productivity of *Eucalyptus* plantations in Zululand, South Africa? South African Forestry Journal. 199: 41-53.

Smith, C.T.; Dyck, W.J.; Beets, P.N.; Hodgkiss, P.D.; Lowe, A.T. 1994. Nutrition and productivity of *Pinus radiata* following harvest disturbance and fertilization of coastal sand dunes. Forest Ecology and Management. 66: 5-38.

Smithwick, E.A.; Harmon, M.E.; Remillard, S.M.; Acker, S.A.; Franklin, J.F. 2002. Potential upper bounds of carbon stores in forests of the Pacific Northwest. Ecological Applications. 12: 1303-1317.

Sollins, P.; Cline, S.P.; Verhoeven, T.; Sachs, D.; Spycher, G. 1987. Patterns of log decay in old-growth Douglas-fir forests. Canadian Journal of Forest Research. 17: 1585-1595.

Sollins, P.; Grier, C.C.; McCorison, F.M.; Cromack, K., Jr.; Fogel, R.; Fredriksen, R.L. 1980. The internal element cycles of an old-growth Douglas-fir ecosystem in western Oregon. Ecological Monographs. 50: 261-285.

Spies, T.A.; Franklin, J.F.; Thomas, T.B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology. 69: 1689-1702.

Startsev, A.D.; McNabb, D.H. 2000. Effects of skidding on forest soil infiltration in west-central Alberta. Canadian Journal of Forest Research. 80: 617-624.

Stein, W.I. 1999. Six-year growth of Douglas-fir saplings after manual or herbicide release from coastal shrub competition. Res. Pap. PNW-RP-500. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Steinbrenner, E.C.; Gehrke, F.E. 1973. Soil survey of the McDonald Tree Farm. Tacoma, WA: Weyerhaeuser Company. 57 p.

Steinbrenner, E.C.; Gessel, S.P. 1955. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Science Society of America Proceedings. 19: 372-376.

Stevens, P.A.; Hornung, M. 1990. Effect of harvest intensity and ground flora establishment on inorganic-N leaching from a Sitka spruce plantation in north Wales, United Kingdom. Biogeochemistry. 10: 53-65.

Sutton, R.F. 1975. Nutrition and growth of white spruce outplants: enhancement by herbicidal site preparation. Canadian Journal of Forest Research. 5: 217-223.

Swank, W.T. 1960. A quantitative analysis of vegetation on the Fern Lake Watershed. Seattle, WA: University of Washington. 90 p. M.F. thesis.

Terry, T.A.; Harrison, R.B.; Harrington, C.A. 2001. Fall River long-term site productivity study: objectives and design. Forestry Research Tech. Note 01-1. Centralia, WA: Weyerhaeuser Company, Western Timberlands Research and Development. 10 p.

Thies, W.G.; Cunningham, P.G. 1996. Estimating large-root biomass from stump and breast-height diameters for Douglas-fir in western Oregon. Canadian Journal of Forest Research. 26: 237-243.

Tingey, D.T.; Phillips, D.L.; Johnson, M.G.; Rygiewicz, P.T.; Beedlow, P.A.; Hogsett, W.E. 2005. Estimates of Douglas-fir fine root production and mortality from minirhizotrons. Forest Ecology and Management. 204: 359-370.

Torbet, H.A.; Wood, C.W. 1992. Effects of soil compaction and water-filled pore space on soil microbial activity and N losses. Communications in Soil Science and Plant Analysis. 23: 1321-1331.

Turner, J; Long, J. 1975. Accumulation of organic matter in a series of Douglas-fir stands. Canadian Journal of Forest Research. 5: 681-690.

U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Staff [USDA NRCS]. 1999. Keys to soil taxonomy, 5th ed. SMSS Tech. Monograph 19. Blacksburg, VA: Pocahontas Press, Inc. 556 p.

U.S. Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center; Oregon State University, University Spatial Climate Analysis Service [USDA OSU]. 1999. Parameter-elevation Regressions on Independent Slopes Model (PRISM). http://www.wcc.nrcs.usda.gov. (7 October 2005).

Valentine, J.M. 1975. Site preparation effects on microclimate and Douglas-fir seedling growth. Seattle, WA: University of Washington. 150 p. Ph.D. dissertation.

Vance, E.D. 2000. Agricultural site productivity: principles derived from long-term experiments and their implications for intensively managed forests. Forest Ecology and Management. 138: 369-396.

Vitousek, P.M.; Gosz, J.R.; Grier, C.C.; Melillo, J.M.; Reiners, W.A. 1982. A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems. Ecological Monographs. 43: 125-143.

Vogt, K.A.; Grier, C.C.; Vogt, D.J. 1986. Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. Advances in Ecological Research. 15: 303-377.

Vogt, K.A.; Vogt, D.J.; Moore, E.E.; Fatuga, B.A.; Redlin, M.R.; Edmonds, R.L. 1987. Conifer and angiosperm fine-root biomass in relation to stand age and site productivity in Douglas-fir forests. Journal of Ecology. 75: 857-870.

Waring, R.H.; McDowell, N. 2002. Use of a physiological process model with forestry yield tables to set limits on annual carbon balances. Tree Physiology. 22: 179-188.

Watt, M.S.; Whitehead, D.; Mason, E.G.; Richardson, B.; Kimberley, M.O. 2003. The influence of weed competition for light and water on growth and dry matter partitioning of young *Pinus radiata*, at a dryland site. Forest Ecology and Management. 183: 363-376.

Weetman, G.F.; Webber, B. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Canadian Journal of Forest Research. 2: 351-369.

Wert, S.; Thomas, B.R. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Science Society of America Journal. 45: 629-632.

Wingate, K.G.; McFarlane, P.N. 2005. Chain of custody and eco-labelling of forest products: a review of the requirements of the major forest certification schemes. International Forestry Review. 7: 342-347.

Wiley, K.N. 1975. Site index for western hemlock in the Pacific Northwest. Forestry Paper 17. Centralia, WA: Weyerhaeuser Company, Western Forestry Research Center. 27 p.

Zabowski, D.; Java, B.; Scherer, G.; Everett, R.L.; Ottmar, R. 2000. Timber harvesting residue treatment: Part 1. Responses of conifer seedlings, soils and microclimate. Forest Ecology and Management. 126: 25-34.

Zabowski, D.; Skinner, M.F.; Rygiewickz, P.T. 1994. Timber harvesting and long-term productivity: weathering processes and soil disturbance. Forest Ecology and Management. 66: 55-68.

Zutter, B.R.; Miller, J.H.; Allen, H.L.; Zedaker, S.M.; Edwards, M.B; Newbold, R.A. 1999. Fascicle nutrient and biomass responses of young loblolly pine to control of woody and herbaceous competitors. Canadian Journal of Forest Research. 29: 917-925.