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The Fall River Long-Term Site Productivity Study in Coastal Washington: Site Characteristics, Methods, and Biomass and Carbon and Nitrogen Stores Before and After Harvest

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Cover Photos (clockwise from top left): 47-year-old stand at Fall River study area with oxalis understory; equipment redistributing branches after forwarding logs on the commercial bole-only removal plot with compaction; assessing coarse woody material left after treatment implementation; a total-tree-plus harvest treatment plot showing the lack of woody material left on site; a commercial bole-only harvest treatment showing the branches and nonmerchantable stem material left on site (fresh needles were also left but had fallen off the branches by the time of the photo); and the weather station installation at the Fall River research area.

Abstract

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The Fall River research site in coastal Washington is an affiliate installation of the North American Long-Term Soil Productivity (LTSP) network, which constitutes one of the world's largest coordinated research programs addressing forest management impacts on sustained productivity. Overall goals of the Fall River study are to assess effects of biomass removals, soil compaction, tillage, and vegetation control on site properties and growth of planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Biomass-removal treatments included removal of commercial bole (BO), bole to 5-cm top diameter (BO5), total tree (TT), and total tree plus all legacy woody debris (TT+). Vegetation control (VC) effects were tested in BO, while soil compaction and compaction plus tillage were imposed in BO+VC treatment. All treatments were imposed in 1999. The preharvest stand contained similar amounts of carbon (C) above the mineral soil (292 Mg/ha) as within the mineral soil to 80-cm depth including roots (298 Mg/ha). Carbon stores above the mineral soil ordered by size were live trees (193 Mg/ha), old-growth logs (37 Mg/ha), forest floor (27 Mg/ha), old-growth stumps and snags (17 Mg/ha), coarse woody debris (11 Mg/ha), dead trees/snags (7 Mg/ha), and understory vegetation (0.1 Mg/ha). The mineral soil to 80-cm depth contained 248 Mg C/ha, and roots added 41 Mg/ha. Total nitrogen (N) in mineral soil and roots (13 349 kg/ha) was more than 10 times the N store above the mineral soil (1323 kg/ha). Postharvest C above mineral soil decreased to 129, 120, 63, and 50 Mg/ha in BO, BO5, TT, and TT+, respectively. Total N above the mineral soil decreased to 722, 747, 414, and 353 Mg/ha in BO, BO5, TT, and TT+, respectively. The ratio of total C above the mineral soil to total C within the mineral soil was markedly altered by biomass removal, but proportions of total N stores were reduced only 3 to 6 percent owing to the large soil N reservoir on site.

Keywords: Sustainable forestry, biomass, C and N stores, organic matter retention, soil physical properties, Andisols, vegetation, climate.

Contents

Study Background and Objectives

Sustainable Forest Management

Private and public land managers are increasingly interested in demonstrating to the public that their forestry practices are sustainable. Strategies such as the "New Forestry" approach (Franklin 1990) developed in the Pacific Northwest region of the United States raised questions about traditional paradigms of forest management and led to changes in the legal and regulatory framework that placed increased emphasis on nontimber forest resources. In 1995, 10 countries including the United States agreed to implement criteria and indicators for sustainable forest management through an international technical working group known as the Montreal Process (Montreal Process 1995). Within this context, a criterion is defined as a forest-related condition or process that characterizes an element of sustainable forest management. Indicators are then developed for each criterion to quantitatively or qualitatively assess current conditions and monitor changes over time. Criteria and indicators are not regulations but a framework for data collection and reporting (McRoberts et al. 2004). Additionally, several types of third-party certification have been developed to provide unbiased assessment of sustainable forest management (Wingate and McFarlane 2005). Every element of sustainable forestry requires generating scientific knowledge on the long-term effects of forest practices on forest ecosystems. This entails using well-designed, multidisciplinary experiments carried out across soil and climatic conditions to fill knowledge gaps.

Intensive forest management practices for increasing wood production and improving operational efficiency may affect forest sustainability, depending on initial site conditions and treatment regimes. Soil compaction caused by equipment traffic and excessive removal of organic matter and nutrients in slash, wood, forest floor, and topsoil have been recognized as two of the major factors potentially leading to site degradation and reduction in forest productivity (Powers 1999, Vance 2000). Practices such as vegetation control, tillage, and fertilization can potentially increase productivity above base levels and ameliorate negative impacts on productivity caused by soil compaction or nutrient removal. Long-term studies are crucial to evaluating management effects on forest productivity across a range of sites. Detailed characterization of initial study conditions is an important component of studies that test the effects of silvicultural and other management treatments on relevant site conditions and long-term site productivity (Harmon and Marks 2002). In this paper, we detail objectives and describe the experimental design and site-characterization methodology used in the long-term site productivity study at Fall River in coastal Washington. We also quantify biomass and carbon (C) and nitrogen (N) stores before and after imposing various biomass-removal treatments.

Biomass Removal Impacts

Long-standing questions still exist about the consequences of increased biomass removals on long-term site productivity. Both harvest intensity and site preparation can affect the amounts of removed biomass. These practices change through time depending upon several driving factors. Traditionally, only the merchantable-bole portion of trees was removed from harvested stands in the Pacific Northwest. The remaining portions of the felled trees along with nonmerchantable trees were left on the site. Residual biomass was often burned to reduce risk of wildfire and to facilitate planting or other management activities. Gradual changes in merchantability standards and harvest technologies, and use of an increased proportion of processed timber from managed plantations have resulted in greater biomass utilization from the Pacific Northwest forests than in the past.

Whole-tree harvesting removes more nutrients from the site than conventional harvesting (Boyle 1976, Egnell and Valinger 2003, Freedman et al. 1981, Weetman and Webber 1972). Slash reduction and site preparation treatments such as piling and broadcast burning also affect site nutrient stores and microsite climate. Both the potential benefits and risks of prescribing amounts and types of forest residues need further quantification and understanding for specific sites. Sites with greater reserves of soil organic matter and nutrients and a favorable climate for plant growth are likely to be more resilient to biomass removals than sites lacking these characteristics. Residue retention can conserve nutrients by reducing nutrient losses from leaching (Blumfield and Xu 2003, Carlyle et al. 1998, Jurgensen et al. 1992). Foliage retained on site may represent a significant source of N for newly-planted seedlings once decomposition of this material occurs. Nitrogen mineralization rates can increase soon after harvest but drop in subsequent years as mineralizable substrate is depleted. Microbial decomposition of woody debris with high C:N ratios, however, can immobilize nutrients such as N making them unavailable for tree growth early in the rotation (Mendham et al. 2003, O'Connell et al. 2004). Residue retention in a radiata pine (*Pinus radiata* D. Don) stand resulted in 43 percent more total N mineralized over 4 years, but much of the mineralized N leached below the rooting zone (Smethurst and Nambiar 1990). In subtropical Australia, retention of residues resulted in reduced net N mineralization and N loss from leaching for 2 years after harvest (Blumfield and Xu 2003). Doubling the amount of harvest residues increased nonsymbiotic N-fixation by 73 percent on conifer sites in the northern Rocky Mountains during 2 years after harvesting (Jurgensen et al. 1992).

Leaching of inorganic N may increase in recent clearcuts compared to mature stands (Sollins et al. 1980, Stevens and Hornung 1990) although in some cases N leaching may remain unchanged (Cole and Gessel 1965, Silkworth and Grigal 1982). Results from 11 forest types across the United States indicated that differences in nitrate losses by leaching between bole-only and whole-tree harvesting were generally small (Mann et al. 1988). In the Pacific Northwest, leaching losses are generally low because of large amounts of organic matter on the forest floor and A horizon, and small populations of nitrifiers (Vitousek et al. 1982). Nevertheless, most investigations assessing the effect of harvest intensity and organic matter removal on N leaching in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands have been performed in low- and medium-productivity forests (Bigger 1988, Compton and Cole 1990). Increased leaching can occur in sites with large soil N stores and low soil C:N ratios (Fenn et al. 1998), although such sites are more resilient and negative effects on plant growth are less likely.

Residue retention usually contributes to the conservation of soil water although effects can be short lived and restricted to the upper soil layers (Blumfield and Xu 2003, O'Connell et al. 2004). Residue retention can also significantly moderate surface soil temperatures. During 18 months following harvest, average soil temperatures in a *Pinus radiata* plantation at 7.5-cm depth in areas where slash and litter were removed were 4 ºC and 1 ºC higher during the summer and winter, respectively, than those in areas with either slash and litter, or litter only (Smethurst and Nambiar 1990). In California, summer temperature of bare soils developed from metabasalt at 15-cm depth was 4.5 ºC warmer than that of soils with an intact forest floor (Powers 2002). At 5-cm depth, soil temperatures at midsummer were 9 to 10 ºC cooler on sites with retained logging slash compared to sites with exposed mineral soil (Valentine 1975). Retention of harvest residues not only resulted in cooler surface soil temperatures but also in smaller diurnal temperature variation in *Eucalyptus globulus* Labill. plantations in southwestern Australia (O'Connell et al. 2004).

Tree growth responses after harvest-residue retention treatments have been variable. Harvest-residue retention had no effect on average height or diameter growth of radiata pine during 3 years following harvest (Smethurst and Nambiar 1990) or on average height of Douglas-fir at age 5 (Smith et al. 1994, Zabowski et al. 2000). Retaining residues significantly improved growth of *E. globulus* seedlings during 7 years on a sandy, low-fertility soil when the amount of harvest residues was doubled (Mendham et al. 2003). In another study, differences in growth of *E. globulus* associated with residue treatments 3 years after harvest were small (Jones et al. 1999), and only incorporation of residues into the soil resulted in a significant tree growth increase. Mean annual increment in height, diameter, and volume of Sitka spruce (*Picea sitchensis* (Bong.) Carr) during 2 years was about 33 percent less with complete residue removal than with bole-only harvest (Proe and Dutch 1994). Impacts on Scots pine (*Pinus sylvestris* L.) growth associated with whole-tree harvesting did not become apparent until several years after harvest on an N-limited site in Sweden (Egnell and Valinger 2003). Biomass removals were most detrimental to tree growth on aspen sites in the Lake States when 10-year study results were summarized for 26 of the oldest installations of the Long-Term Soil Productivity (LTSP) network sites (Powers et al. 2005). Although these investigations quantified short-term effects of residue treatments, long-term consequences remain uncertain.

Effects of Competing Vegetation

Shrub and herbaceous vegetation can influence stand establishment and growth by competing with trees for limited resources. Positive effects of competition control on seedling growth have been associated with increased soil water availability (Flint and Childs 1987, Newton and Preest 1988, Watt et al. 2003), nutrients (Smethurst and Nambiar 1995, Zutter et al. 1999), or both (Elliott and White 1987, Powers and Reynolds 1999). Douglas-fir seedlings responded positively to reductions in cover or biomass of competing vegetation (Dimock et al. 1983, Miller and Obermeyer 1996, Roberts et al. 2005, Stein 1999), but few studies have correlated growth responses to changes in resource availability or uptake. Average increases of 16 percent in bole diameter of Douglas-fir seedlings were recorded after 2 years of chemical release from shrub competition on a loamy-skeletal Typic Xerochrept in a dry site in southwest Oregon (Flint and Childs 1987). Growth gains were attributed primarily to increased moisture available to seedlings. On a moist, well-drained site in coastal Oregon, control of herbaceous vegetation induced wood volume increases from 80 to 200 percent at age 5 that correlated with decreased plant drought stress (Newton and Preest 1988). Competing vegetation around 1-year-old Douglas-fir seedlings in northern Idaho increased moisture stress and decreased seedling growth (Eissenstat and Mitchell 1983), but other environmental factors may have limited seedling growth as well.

Nutrient limitations commonly occur in established Douglas-fir stands throughout the Pacific Northwest (Gessel et al. 1990). Competing vegetation can affect nutrient availability in young coniferous stands. Because reduced nutrient availability often occurs in conjunction with water limitations, it can be difficult to separate the two effects (Ludovici and Morris 1997, Morris et al. 1993, Powers and Reynolds 1999). Seedling height and volume significantly increased over the first 3 years in white spruce (*Picea glauca* (Moench) Voss) plantations subjected to vegetation control (Sutton 1975). Growth increases were correlated with increased foliar nutrient concentrations, although improved moisture conditions were also noted. Nutrient limitations were considered more important than moisture limitations for pine seedlings growing on coastal flatwood sites of the Southeastern United States (Neary et al. 1984), but the significance of competing vegetation effects on nutrient availability may decrease as site nutrient availability increases (Morris et al. 1993).

Impacts of Ground-Based Harvesting

Ground-based forest operations can affect soil physical (Lenhard 1986, Startsev and McNabb 2000), chemical (Herbauts et al. 1996, Zabowski et al. 1994), and biological (Dick et al. 1988, Smeltzer et al. 1986, Torbet and Wood 1992) characteristics. Effects of intensive harvest and site preparation on soil properties and tree growth can be positive, detrimental, or inconsequential (Miller et al. 2004). Soil compaction (Hatchell et al. 1970, Steinbrenner and Gessel 1955), usually indexed by bulk density or soil strength measurements (Greacen and Sands 1980, Powers et al. 1998), reduces tree growth under certain conditions (Conlin and van den Driessche 1996, Froehlich et al. 1986, Murphy 1983, Wert and Thomas 1981). On some sites, however, soil compaction has resulted in increased tree growth, probably because of increased water-holding capacity (Ares et al. 2005, Gomez et al. 2002b), unsaturated waterflow (Sands et al. 1979), root contact with soil (Bhadoria 1986), and N uptake (Gomez et al. 2002a). Recent studies have revealed a large degree of site specificity both in soil and tree growth responses to soil compaction (Brais 2001, Gomez et al. 2002b, Heninger et al. 1997, Smith 2003).

Most studies in the Pacific Northwest region of the United States and elsewhere have assessed changes in soil characteristics, tree growth, and site productivity on logged sites using the “after-the-fact” retrospective approach in which management impacts are studied in operational stands under noncontrolled conditions (Powers 1989). This approach may not determine the original type, degree, and extent of disturbance. In addition, tree growth could have been unknowingly and differentially affected by plant competition, disease, herbivory, and other factors (Heninger et al. 1997). Previous research also illustrates the risk associated with extrapolating early short-term treatment responses to rotation age. To understand the mechanisms underlying tree growth responses to treatments across a range of sites requires replicated studies lasting until stand rotation age or even through more than one rotation. These studies should follow sound methodological approaches with imposed treatments representing field forest operations as closely as possible. With these purposes in mind, the study at Fall River was initiated in 2000.

The Fall River study is an affiliate installation of the U.S. Forest Service Long-Term Soil Productivity research program.

Research Objectives

The Fall River study is one of the more than 40 affiliate installations of the LTSP program initiated in 1989 by the U.S. Forest Service and several collaborating organizations on major soil and vegetation types of the United States and Canada (Powers and Fiddler 1997). The main hypothesis for this research program is that site organic matter and soil pore space are the critical site characteristics affected by forest operations that influence long-term site productivity (Powers et al. 2005). Although the LTSP program includes a large set of long-term site productivity studies, none of the main trials was located in the Pacific Northwest when the Fall River study was initiated. Affiliate studies should have at least three treatments in common with the main study design, one of which must be a control (i.e., no compaction, minimal organic matter removal). The Fall River study is a long-term, replicated experiment in which imposed disturbances reflect field operational conditions as closely as possible and confounding effects of big-game browse and unknown site history have been removed. In addition, the experimental site has homogenous soil and topographic conditions, and relatively low levels of root-rot diseases.

The main goal of the Fall River study is to understand how ground-based forest harvest, slash/wood removal, vegetation management, and fertilization influence soil and tree processes and long-term site productivity on a highly productive site in coastal Washington. Specific study objectives include to (1) determine the effects of four levels of biomass removals on soil properties and processes and on Douglas-fir aboveground growth; (2) develop C and nutrient budgets for various levels of biomass removals; (3) determine the impacts of soil disturbance and compaction on soil properties and aboveground tree growth and the effectiveness of tillage in maintaining or enhancing site productivity; (4) assess the effects of vegetation control on understory plant cover, plant species composition, aboveground tree growth, and water and nutrient status; (5) determine the need for fertilization to ameliorate nutrient removals and its effects on nutrient supply and aboveground tree growth; and (6) evaluate differences in microclimate and seedling physiology across microsites within the study treatments. Study treatments include different levels of woody debris and residual biomass retention, vegetation and nutrient management, and soil disturbance before planting Douglas-fir seedlings. Knowledge generated in this study will help to improve forest management prescriptions across the range of sites found in the Pacific Northwest. This study deals with the so-called "narrow-sense" sustainability (Evans 1999) that focuses on changes induced by planted forests on tree productivity and site conditions over time, and on silvicultural interventions needed to sustain and enhance wood production.

The main objective of this paper is to document the biomass and C and N stores in the Douglas-fir/western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stand before treatment installation and after imposing the four treatments described in the "Biomass-Removal Treatments" section. This baseline information will be useful in comparing results from the Fall River study with those from other research projects and should help investigators understand the mechanisms of short- and long-term response to experimental treatments. It will also be valuable for scientists who may wish to carry the study through repeated cycles and multiple rotations to examine changes in the stores and in their effects on long-term site productivity. Other objectives are to describe the research site characteristics, study design, and treatment implementation.

Study Layout

Site Selection Criteria

Several criteria were used to choose the Fall River site for this study. Selection criteria included (1) site representative of areas in western Washington that are being intensively managed for Douglas-fir plantations and conducive to ground-based harvesting; (2) soils minimally disturbed by previous ground-based harvesting operations and with volcanic parent material, which commonly occurs in western Washington; (3) high site quality for Douglas-fir (Class II or better according to King 1966); (4) Douglas-fir stand with known site treatment history; (5) site without any evident areas of root diseases that could cause irregular tree mortality after planting; (6) site sufficiently large and uniform to allow the installation of forty-eight 0.25-ha treatment plots with additional space for buffers to accommodate logging traffic and removed woody debris; and (7) site located within reasonable travel-time distance for the personnel of Weyerhaeuser Co., U.S. Forest Service, and University of Washington participating in the study. Of the several tentative sites preselected and screened, the Fall River site best met these selection criteria.

Location and Experimental Design

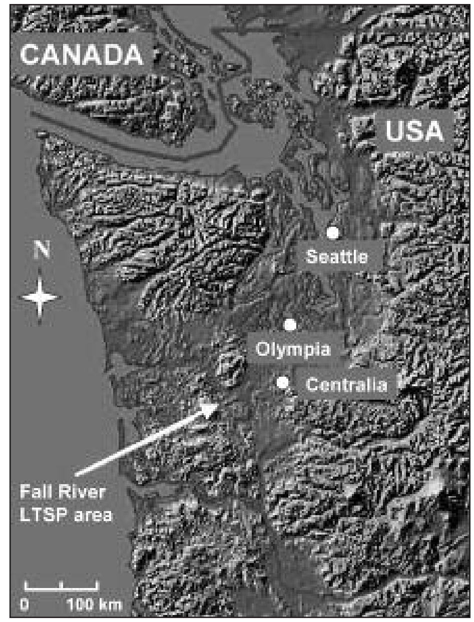

Figure 1—Location of the Fall River research area in coastal Washington.

The study site is located at 46° 43' N and 123° 25' W in the Twin Harbors-South operating area of Weyerhaeuser Company in Pacific County, Washington, within the Fall River drainage (fig. 1). The Fall River study will ultimately contain 12 treatments in a randomized complete block design with four replicates (Terry et al. 2001) (table 1 and fig. 2). Seven of the treatments were implemented in 1999; treatments involving fertilization with 220 kg N/ha will be imposed in the future. Treatment plots are 30 by 85 m (0.25 ha) with an internal 15- by 70-m (0.10 ha) measurement plot. Experimental blocking was based on slope position and percentage of the stand in Douglas-fir and western hemlock. Blocks 1 and 2 were on gentle upper slopes, and blocks 3 and 4 were on gentle lower slopes. Blocks 3 and 4 were immediately below blocks 1 and 2 topographically, but separated by a buffer large enough to accommodate harvesting equipment traffic and slash and woody debris piles. Blocks 1 and 2 had more total wood volume in Douglas-fir (58 and 69 percent of the total volume) than blocks 3 and 4 (49 and 43 percent); the remaining wood volume in all blocks was western hemlock.

Site Characterization

Climate

The Fall River research site is within the cool temperate moist Holdridge Life Zone (Lugo et al. 1999) and has a maritime climate with mild wet winters and warm dry summers. Estimated mean annual precipitation is 2260 mm, mostly as rain (Daly et al. 1994, USDA and OSU 1999). Summers are much drier than winters with an average rainfall of only 240 mm from June 1 to September 30. Summer dry periods result from the combined effect of the jet stream moving rainy frontal systems to the north, and a subtropical high-stabilizing front off the Washington coast. This high-pressure area produces an onshore airflow that is warmer than the sea surface, and creates vast fog banks but little rain. Mean annual air temperature at Fall River

Table 1—Treatment and plot assignment in the long-term site productivity study at Fall River

Treatment[a]	Harvest level	Fertilizer	Vegetation control	Soil compaction	Soil tillage	Plots in blocks 1	2	3	4
1	Commercial bole only (BO)		x			1	22	29	45
2	Commercial bole only (BO)	x	x			11	20	33	50
3	Bole only to 5-cm top (BO5)		x			6	13	30	44
4	Bole only to 5-cm top (BO5)	x	x			7	18	25	46
5	Total tree (TT)		x			2	15	28	53
6	Total tree (TT)	x	x			8	16	32	42
7	Total tree plus (TT+)		x			3	14	34	41
8	Total tree plus (TT+)	x	x			5	24	36	43
9	Commercial bole only (BO)					9	23	26	47
10	Commercial bole only (BO)	x				10	21	31	49
11	Commercial bole only (BO)	x	x	x		4	17	35	51
12	Commercial bole only (BO)	x	x	x	x	12	19	27	48

[a] Fertilizer treatments have not been installed as of 2006, but they may be applied in the future. Biomass-removal, and soil compaction/tillage treatments were installed in 1999, and vegetation control treatments were first applied in 2000. See text for treatment descriptions.

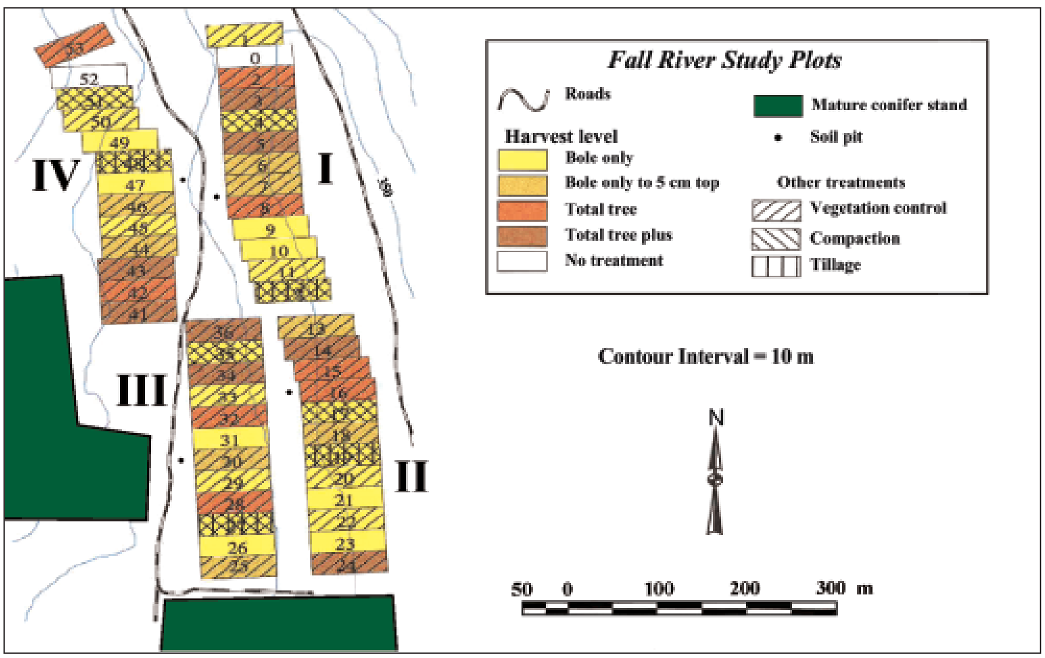

Figure 2—Plot and treatment assignments at the Fall River research area. Plots 0, 37 to 40, and 52 were not used in the study because of irregularities.

is 9.2 ºC, and monthly mean temperatures are 2.6 ºC in January and 16.0 ºC in August (USDA and OSU 1999).

An automated weather station was installed in 2000 at Fall River to provide onsite information. The station was located approximately in the middle of the Fall

River research site and in a buffer area between blocks 1 and 2 that did not receive vegetation control. The station records air temperature and relative humidity with a Vaisala HMP45C probe[1] (Vaisala, Vaanta, Finland), precipitation with a 20.3-cm diameter TE5252 tipping bucket rain gauge (Texas Electronics), global solar radiation with a LI-200 SZ pyranometer (LI-COR), wind direction and speed with a Wind Sentry 03002 probe (R.M. Young, Traverse City, MI), soil temperature at 10-, 20-, and 50-cm depths with "T" thermocouples and soil water content at 10- and 50-cm depths with CS615 probes (Campbell Scientific) (tables 2 through 4). Air temperature, relative humidity, rainfall, global solar radiation, and wind direction and speed are recorded at 2 m above ground (tables 2 and 3). Air temperature is also recorded at 25-cm above ground with a "T" thermocouple. Measurements are taken at 3-second intervals and hourly averages and totals are stored in a CR-10X data logger (Campbell Scientific). Pertinent climatic data from 2000 to 2005 are summarized in tables 2, 3, 4 and 5. Mean maximum values for air and soil temperature, soil water content, and vapor pressure deficit are averages of the maximum values recorded in a given day (tables 2 through 5).

In recent years, mean annual precipitation at Fall River has been consistently below the estimated historical average. Since meteorological monitoring began in 2000 at Fall River, the greatest annual precipitation (1973 mm) was recorded in 2003, followed in decreasing order by 1794 mm in 2005, 1608 in 2001, 1522 mm in 2004, and 1388 in 2002 (fig. 3). Relatively high precipitation for a year or even during a whole growing season (i.e., the period between the start of shoot development and the cessation of tree stem growth, usually May to October), however, does not always correspond to a short summer dry season. In 2003, 33 percent of the rainfall fell during the growing season (651 mm) but only 20 mm was recorded for July and August. In contrast, 42 percent of the annual rainfall occurred during the growing season in 2001 (675 mm) with 103 mm recorded for July and August. Mean maximum vapor pressure deficits were low with a maximum of 0.8 kPa June through August of 2003 (table 5). This indicates a relatively low atmospheric evaporative demand at Fall River.

Vegetation

The Fall River site is within the western hemlock vegetation zone (Franklin and Dyrness 1973). Understory vegetation communities at Fall River were first assessed

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 2—Air temperatures (measured at 25-cm height) and soil temperatures (measured at 10-cm depth) from March 2000 to December 2005 at the Fall River weather station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
						Mean daily air temperature (°C)							
2000			5.9	10.0	9.6	12.5	16.0	16.1	14.5	10.7	4.9	4.1	
2001	4.8	3.7	6.0	6.6	11.1	10.8	13.1	14.6	12.9	7.8	5.6	2.5	8.3
2002	2.1	3.2	2.5	6.3	8.2	12.9	15.1	14.7	12.8	8.6	6.6	3.5	8.0
2003	5.9	2.9	5.0	5.8	9.1	13.9	16.1	15.1	14.3	9.8	3.0	2.7	8.6
2004	3.5	4.2	6.0	9.2	10.3	14.1	17.0	16.5	12.3	8.8	4.3	3.4	9.1
2005	3.7	4.0	6.6	7.1	11.7	12.1	15.4	15.9	11.4	8.8	2.9	2.3	8.5
						Mean daily maximum air temperature (°C)							
2000			13.7	19.5	18.7	21.9	27.4	27.3	23.6	17.5	10.2	8.4	
2001	9.3	10.2	13.0	14.6	20.6	19.7	23.7	25.8	23.4	14.5	10.6	6.4	16.0
2002	5.3	8.6	8.6	14.2	17.4	23.6	27.8	27.5	24.0	17.2	13.5	7.5	16.3
2003	10.8	10.0	11.1	14.3	21.2	26.6	32.5	31.8	28.5	20.0	10.4	7.7	18.8
2004	7.4	12.9	16.2	23.0	22.8	27.2	32.8	31.7	26.4	19.3	12.5	9.1	20.1
2005	10.2	16.6	18.3	18.5	24.0	26.3	30.5	32.4	28.2	19.1	11.1	8.5	20.3
						Mean daily minimum air temperature (°C)							
2000			1.0	4.1	4.4	6.6	8.6	9.6	8.8	5.5	1.3	1.2	
2001	1.0	-0.5	1.1	1.9	3.9	4.6	7.1	8.0	6.3	3.1	2.1	-0.4	3.2
2002	-1.0	-0.9	-1.5	1.1	2.2	5.8	7.4	6.8	5.4	2.9	2.1	0.4	2.6
2003	2.3	-1.3	1.2	0.9	2.3	6.3	6.8	5.7	6.6	5.1	-1.2	-0.8	2.8
2004	.5	0.0	0.2	1.0	3.4	6.1	8.2	9.6	5.9	3.5	0.0	-0.6	3.1
2005	.1	-2.2	0.5	1.5	5.7	5.8	6.8	7.4	4.0	3.8	-1.3	-1.0	2.6
						Mean daily soil temperature (°C)							
2000						15.0	18.1	18.8	16.4	11.6	6.1	4.6	
2001	4.7	4.3	6.8	8.4	12.8	13.6	16.1	15.6	13.7	9.5	6.8	3.0	9.6
2002	3.6	3.2	3.5	7.5	9.6	13.9	15.8	15.5	13.6	9.9	6.8	4.5	9.0
2003	5.6	4.1	6.0	7.7	10.9	15.0	18.0	17.1	14.8	11.3	4.4	3.2	9.8
2004	3.4	4.3	6.8	9.7	12.3	15.0	18.1	17.8	13.9	10.6	6.1	4.6	10.2
2005	3.6	4.3	7.4	8.6	12.8	13.1	15.2	15.8	12.7	10.5	5.0	3.4	9.5
						Mean daily maximum soil temperature (°C)							
2000						19.7	21.4	21.4	19.7	15.3	10.4	6.7	
2001	5.4	5.4	8.3	10.1	15.3	15.8	18.1	17.0	14.9	10.3	7.4	3.6	11.0
2002	4.1	4.0	4.5	9.1	11.1	15.8	17.5	16.9	14.9	10.8	7.5	5.1	10.1
2003	6.3	5.0	7.1	9.2	13.0	17.4	21.3	20.2	17.5	12.9	5.5	4.0	11.6
2004	4.2	5.7	8.6	12.4	14.4	17.8	21.0	20.3	16.0	12.3	7.3	5.5	12.1
2005	4.3	6.1	9.3	10.6	15.0	14.9	16.9	17.4	14.2	11.4	5.8	4.0	11.0
						Mean daily minimum soil temperature (°C)							
2000						10.9	14.8	16.6	14.0	8.7	3.7	2.1	
2001	4.0	3.3	5.7	6.9	10.8	11.8	14.4	14.3	12.6	8.8	6.2	2.5	8.4
2002	3.1	2.4	2.7	6.3	8.3	12.4	14.4	14.2	12.3	9.1	6.0	4.0	7.9
2003	4.8	3.2	5.1	6.5	9.3	13.1	15.5	14.7	12.7	9.9	3.5	2.6	8.4
2004	2.6	3.2	5.2	7.4	10.5	12.9	16.1	15.8	12.2	9.2	5.0	3.8	8.7
2005	3.0	3.0	5.9	7.0	11.2	11.8	13.9	14.6	11.5	9.7	4.4	3.0	8.4

Note: Weather station probes are over or under herbaceous vegetation in areas that were harvested in 1999 and planted in 2000.

Table 3—Windspeed and solar radiation measured at 2 m above ground at the Fall River weather station from March 2000 to December 2005

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Mean daily maximum windspeed (*m/s*)													
2000			6.8	7.6	8.5	7.9	7.3	6.9	6.8	6.8	7.0	9.1	
2001	8.5	8.0	8.1	8.0	8.0	7.4	6.7	6.2	6.1	7.8	8.5	10.5	7.8
2002	8.5	8.9	8.4	8.3	7.3	7.2	6.7	6.8	6.7	6.0	6.7	9.1	7.6
2003	8.6	6.5	9.1	7.6	7.1	7.1	6.7	6.0	6.3	7.6	7.8	8.1	7.4
2004	7.4	8.2	7.7	7.0	6.5	6.1	5.9	5.5	5.7	5.7	5.4	6.3	6.4
2005	6.7	6.1	7.2	6.5	5.8	5.4	4.8	4.6	4.3	4.3	4.9	5.7	5.5
Highest maximum windspeed (*m/s*)													
2000			13.2	10.5	13.7	11.0	9.5	10.0	11.0	14.0	13.7	20.2	
2001	14.0	12.7	15.5	13.0	13.7	10.7	8.7	9.0	10.7	15.2	16.0	19.0	13.2
2002	16.7	15.7	17.0	18.2	10.0	12.2	10.0	10.0	9.5	10.5	12.7	19.7	13.5
2003	20.0	11.5	17.0	12.2	10.5	11.0	13.2	9.0	9.7	15.0	15.2	16.2	13.4
2004	15.0	14.2	13.0	11.7	8.7	9.2	8.0	8.7	10.0	9.5	10.5	11.5	10.8
2005	10.7	11.0	15.0	11.4	10.0	9.0	7.0	6.4	6.2	7.7	11.0	11.0	15.0
Lowest maximum windspeed (*m/s*)													
2000			0.2	4.5	5.5	5.0	5.0	4.7	5.0	3.7	3.2	3.7	
2001	4.2	4.7	4.2	5.2	5.0	5.5	3.2	4.2	3.2	4.0	4.2	4.7	4.3
2002	3.2	4.5	4.5	4.5	4.5	5.5	4.7	3.5	4.0	3.0	3.7	3.7	4.1
2003	3.7	3.5	4.7	4.0	4.7	4.5	5.2	4.2	3.7	2.7	3.2	3.7	4.0
2004	3.7	3.5	4.0	5.0	4.0	3.2	4.7	3.7	2.7	2.7	2.2	2.7	3.5
2005	2.7	3.0	3.7	3.4	3.0	3.0	3.4	3.2	2.7	2.4	2.2	2.0	2.0
Mean daily solar radiation (MJ/m^2 *per day*)													
2000			10.1	15.8	16.1	18.5	21.8	19.0	13.5	9.1	5.0	3.2	
2001	4.1	8.0	10.0	13.8	21.2	18.4	19.9	17.5	14.5	7.5	3.9	2.9	11.8
2002	2.2	7.0	8.3	13.6	15.9	20.1	21.4	19.8	15.1	9.4	5.4	2.8	11.8
2003	4.0	7.5	8.3	13.1	18.0	21.6	24.8	19.9	14.8	7.4	4.6	2.9	12.2
2004	3.2	6.7	10.7	17.9	15.9	21.8	22.6	17.5	13.3	8.5	5.0	3.2	12.5
2005	3.8	10.0	11.1	13.6	17.2	17.5	21.9	20.3	14.9	7.0	4.4	3.3	12.2
Highest daily solar radiation (MJ/m^2 *per day*)													
2000			21.5	24.6	27.5	32.6	32.7	29.5	24.7	19.7	9.6	6.5	
2001	9.1	14.9	20.3	25.4	30.9	31.5	31.8	27.9	21.9	16.6	9.8	6.8	20.6
2002	4.9	14.8	16.3	26.9	28.9	30.9	30.5	27.3	22.5	15.2	11.2	6.4	19.7
2003	8.2	14.8	17.8	25.7	29.7	32.5	31.2	28.0	23.7	14.6	10.7	6.7	20.3
2004	6.4	12.5	20.5	28.0	30.3	32.9	30.3	28.0	22.4	16.9	9.8	6.3	20.3
2005	7.2	14.4	20.2	26.1	31.6	31.7	30.4	28.1	21.9	13.4	7.7	6.3	31.7
Lowest daily solar radiation (MJ/m^2 *per day*)													
2000				2.5	6.6	7.1	8.5	7.8	4.9	1.9	1.1	.6	
2001	1.0	2.3	2.3	5.4	5.5	8.4	5.7	3.3	2.9	1.8	.6	.3	3.3
2002	.2	1.5	2.3	4.1	5.1	5.3	8.4	6.5	4.7	2.5	.9	.7	3.5
2003	.8	2.5	1.8	3.6	6.8	6.3	13.5	6.6	3.0	.9	.5	.7	3.9
2004	.9	1.8	4.1	7.0	7.2	6.2	11.3	6.1	5.6	2.0	1.0	.7	4.5
2005	.6	2.6	1.8	5.5	3.6	6.5	5.6	6.3	2.1	2.5	1.2	.5	3.2

Note: The weather station is in a clearing surrounded by Douglas-fir planted in 2000.

Table 4—Soil water content at 10- and 50-cm depths (vegetated soil condition) from June 2001 to December 2005 at the Fall River weather station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
10-cm depth					Mean daily volumetric soil water content (m^3/m^3)								
2001						0.40	0.35	0.35	0.36	0.41	0.45	0.46	
2002	0.47	0.47	0.46	0.45	0.43	.39	.35	.31	.31	.33	.40	.46	0.40
2003	.47	.46	.49	.47	.44	.37	.31	.30	.33	.43	.47	.47	.42
2004	.48	.47	.46	.43	.43	.42	.32	.34	.41	.44	.45	.47	.43
2005	.48	.46	.47	.48	.45	.43	.40	.31	.31	.40	.46	.47	.43
					Mean daily maximum soil water content (m^3/m^3)								
2001						.41	.35	.35	.36	.42	.46	.48	
2002	.48	.48	.47	.46	.44	.40	.35	.31	.31	.33	.40	.47	.41
2003	.48	.47	.51	.49	.45	.37	.31	.30	.33	.44	.49	.49	.43
2004	.50	.48	.47	.44	.44	.42	.32	.34	.42	.45	.46	.49	.44
2005	.50	.47	.48	.49	.47	.44	.40	.31	.32	.41	.47	.48	.44
					Mean daily minimum soil water content (m^3/m^3)								
2001						.39	.35	.34	.36	.40	.44	.46	
2002	.46	.46	.45	.44	.43	.39	.35	.31	.31	.33	.39	.45	.40
2003	.45	.45	.47	.46	.43	.36	.31	.30	.33	.41	.46	.46	.41
2004	.47	.46	.45	.43	.42	.41	.32	.33	.41	.43	.44	.47	.42
2005	.48	.45	.46	.47	.44	.43	.39	.31	.31	.40	.45	.46	.42
50-cm depth					Mean daily volumetric soil water content (m^3/m^3)								
2001							.39	.39	.40	.42	.48	.50	
2002	.50	.50	.49	.48	.45	.42	.38	.34	.34	.36	.42	.47	.43
2003	.47	.47	.49	.47	.44	.40	.35	.33	.34	.42	.47	.47	.43
2004	.48	.47	.46	.44	.43	.43	.36	.36	.43	.44	.45	.46	.43
2005	.47	.45	.46	.46	.45	.42	.41	.35	.34	.43	.46	.47	.43
					Mean daily maximum soil water content (m^3/m^3)								
2001							.39	.39	.40	.42	.49	.51	
2002	.51	.51	.50	.48	.45	.42	.39	.34	.34	.36	.42	.48	.43
2003	.49	.47	.51	.48	.44	.40	.35	.33	.35	.44	.48	.48	.43
2004	.50	.48	.47	.44	.43	.43	.36	.36	.43	.45	.46	.47	.44
2005	.48	.45	.46	.47	.45	.42	.41	.35	.35	.43	.47	.48	.43
					Mean daily minimum soil water content (m^3/m^3)								
2001							.38	.38	.40	.42	.47	.49	
2002	.49	.49	.48	.47	.45	.42	.38	.34	.34	.36	.41	.46	.42
2003	.47	.46	.48	.47	.44	.40	.35	.33	.34	.41	.45	.46	.42
2004	.47	.46	.46	.44	.42	.42	.36	.36	.42	.44	.44	.46	.43
2005	.46	.44	.45	.46	.44	.41	.41	.35	.34	.42	.46	.46	.42

Table 5—Mean maximum vapor pressure deficit from March 2000 to December 2005 at Fall River

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
	Kilopascals												
2000			0.36	0.48	0.38	0.48	0.75	0.63	0.52	0.52	.26	.20	
2001	0.25	0.26	.28	.29	.65	.47	.55	.64	.61	.33	.24	.18	0.40
2002	.12	.25	.20	.34	.41	.63	.76	.78	.68	.44	.37	.17	.43
2003	.26	.24	.19	.28	.42	.79	.79	.79	.75	.26	.17	.14	.42
2004	.09	.24	.28	.61	.37	.67	.80	.59	.38	.29	.16	.13	.38
2005	.16	.38	.34	.30	.47	.39	.65	.75	.51	.21	.13	.13	.37

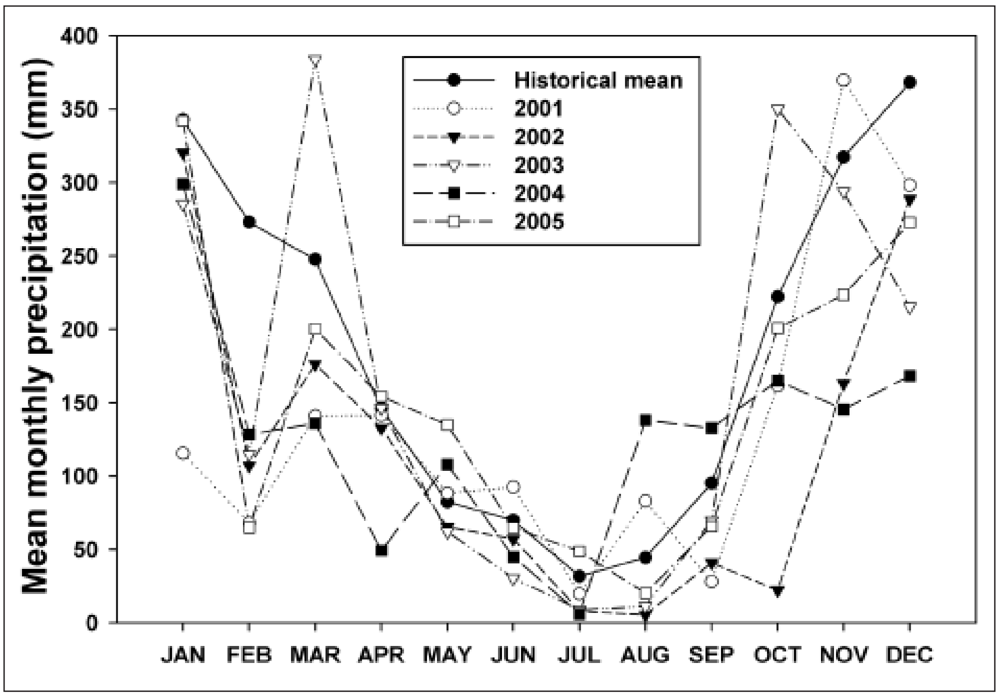

Figure 3—Total monthly precipitation recorded at a weather station at the Fall River research area from 2001 to 2005, and historical monthly means estimated with the PRISM program (USDA OSU 1999).

in late summer of 1998 within the 48-plot area before harvest.[2] The objectives of that vegetation analysis were to determine the most representative plant associations and to identify the most common understory species present at the study site. The low-intensity vegetation survey used standard methods (Bonham 1989). Vegetation was assessed in one randomly chosen sampling plot per each of the 48 treatment plots along an arbitrary 315° bearing. The bearing was randomly changed when it placed the sampling point outside the plot, or if it was obstructed by a tree,

[2] E. Beach. 2001. Unpublished data, on file with Thomas Terry, Weyerhaeuser Company, Centralia, WA 98531

old-growth stump, or large woody debris. Ground vegetation data recorded for each sampling plot consisted of a visual cover estimate for each vascular plant species present within a 1-m^2 quadrat. Cover was defined as the vertically projected area of all aboveground plant parts. Forest plant associations present on the site were determined by using the *Forested Plant Associations of the Olympic National Forest* (Henderson et al. 1989) as a source document.

Cover values within plots ranged from 0 to 90 percent with a mean cover of 48 percent. Species richness ranged from one to four vascular plant species per plot (mean = 1.9). A total of 15 understory species were tallied during the survey, excluding tree seedlings (table 6). Vine maple (*Acer circinatum* Pursh) was not found in the sample plots, but does occur in scattered clumps within the study area. At least 17 other species of shrubs, ferns, and herbs are also present in the area (table 6). The predominant plant association before logging was western hemlock/western sword fern (*Polystichum munitum* (Kaulf.) K. Presl.)/oxalis (*Oxalis oregana*) Nutt. (Henderson et al. 1989). Mean cover of *O. oregana* and *P. munitum* was 39 percent and 7 percent, respectively. Based on a chi-square distance measure, species and samples were ordinated simultaneously and five species assemblages were determined by correspondence analysis (table 7).

Geology and Geomorphology

The study site is on gentle slopes (averaging 10 to 15 percent) facing west within the Willapa Hills physiographical province in the Coast Range of Washington (fig. 4). The site is about 56 km from the Pacific Ocean and elevations range between 305 and 362 m. This coastal uplifted province is situated between the Olympic Mountains to the north, the Columbia River to the south, the Pacific Ocean to the west, and the Cascade Mountains to the east. The Willapa Hills province includes the Black Hills, the Doty Hills, and the adjacent broad valleys that open up to the Pacific Ocean. The Willapa Hills have rounded topography and rise to 945 m elevation.

Thick sequences of sedimentary and volcanic rocks of Eocene through Miocene age are present (Lasmanis 1991) (fig. 5). The Crescent Formation basalts from the middle and late Eocene (35 to 50 million years ago) underlie McIntosh marine sandstones from the same geological period (Christiansen and Yeats 1992). On top of McIntosh sandstones, there are Lincoln Creek marine sandstones from the late Eocene and Oligocene (25 to 54 million years ago). The early and middle Miocene periods (7 to 15 million years ago) are represented by Astoria and Montesano marine sandstones, and Pomona and Grande Ronde basalts that flowed

Table 6—Cover and frequency estimates[a] of plant species at Fall River in 1998

Common name	Scientific name	Cover	Range	Frequency[b]
		- - - - -*Percent* - - - - -		
Oxalis	*Oxalis oregana* Nutt.	38.7 (29.4)	0-90	0.88
Swordfern	*Polystichum munitum* (Kalfuss) K. Presl	6.8 (15.5)	0-85	.33
Spiny woodfern	*Dryopteris expansa* (K. Presl) Fraser-Jenkins & Jeremy	.9 (3.4)	0-20	.08
Deer fern	*Blechnum spicant* (L.) Sm.	.5 (2.2)	0-14	.11
Ladyfern	*Athyrium filix-femina* (L.) Roth	.3 (1.4)	0-8	.04
Oregon grape	*Mahonia nervosa* (Pursh) Nutt.	.3 (1.5)	0-10	.04
Blackberry	*Rubus ursinus* Cham. & Schlecht.	.2 (1.5)	0-10	.02
Inside-out flower	*Vancouveria hexandra* (Hook.) Morr. & Dcne.	.2 (0.8)	0-5	.06
Trailing yellow violet	*Viola sempervirens* Greene	.2 (0.5)	0-2	.15
Salmonberry	*Rubus spectabilis* Pursh	.1 (0.5)	0-3	.02
Western starflower	*Trientalis borealis* Raf.	.1 (0.3)	0-2	.04
Cascara buckthorn	*Frangula purshiana* DC.	< .1	0-1	.02
Smith's fairybells	*Disporum smithii* (Hook.) Piper	< .1	0-1	.02
Vanilla leaf	*Achlys triphylla* (Sm.) DC.	< .1	0-1	.02
Sweet-scented bedstraw	*Galium triflorum* Michx.	< .1	0-0.5	.02

Values for cover are means ± one standard deviation in parentheses (n = 48 plots).

[a] Based on a survey with a small sample size.

[b] Frequency = proportion of plots in which a species occurred.

The following species were also present in the preharvest stand in an additional survey carried out in 2001: vine maple (*Acer circinatum* Pursh), angelica (*Angelica genuflexa* Nutt.), Dewey sedge (*Carex deweyana* Schwein.), Pacific bleeding heart (*Dicentra formosa* (Haw.) Walp.), western fescue (*Festuca occidentalis* Hook.), crinkleawn fescue (*Festuca subuliflora* Scribn.), white hawkweed (*Hieracium albiflorum* Hook.), smallflowered woodrush (*Luzula parviflora* (Ehrh.) Desv.), false lily (*Maianthemum dilatatum* (Wood) A. Nels. & J.F. Macbr.), false azalea (*Menziesia ferruginea* Sm.), candy flower (*Claytonia sibirica* L.), devil's club (*Oplopanax horridus* Miq.), wood rose (*Rosa gymnocarpa* Nutt.), red elderberry (*Sambucus racemosa* L.), western brackenfern (*Pteridium aquilinum* (L.) Kuhn), Pacific trillium (*Trillium ovatum* Prush), Alaska blueberry (*Vaccinium ovalifolium* Sm.), and red huckleberry (*Vaccinium parvifolium* Sm.) (D. Peter, 2005, personal communication, Ecologist, PNW Research Station).

Table 7—Dominant plant species in five assemblies determined with TWINSPAN[a] at the Fall River pretreatment survey

Assembly code	Common species
OXOR-POMU-BLSP	*Oxalis oregana, Polystichum munitum, Blechnum spicant*
OXOR-VAHE	*Oxalis oregana, Vancouveria hexandra*
OXOR-POMU	*Oxalis oregana, Polystichum munitum*
OXOR-DRAU	*Oxalis oregana, Dryopteris austriaca*
VISE-BLSP	*Viola sempervirens, Blechnum spicant*

[a] TWINSPAN is a program for classifying species and samples. It is available from the Centre for Ecology and Hydrology, United Kingdom. www.ceh.ac.uk/products/software/CEHsoftware-DECORANATWINSPAN.htm, (July 19, 2006).

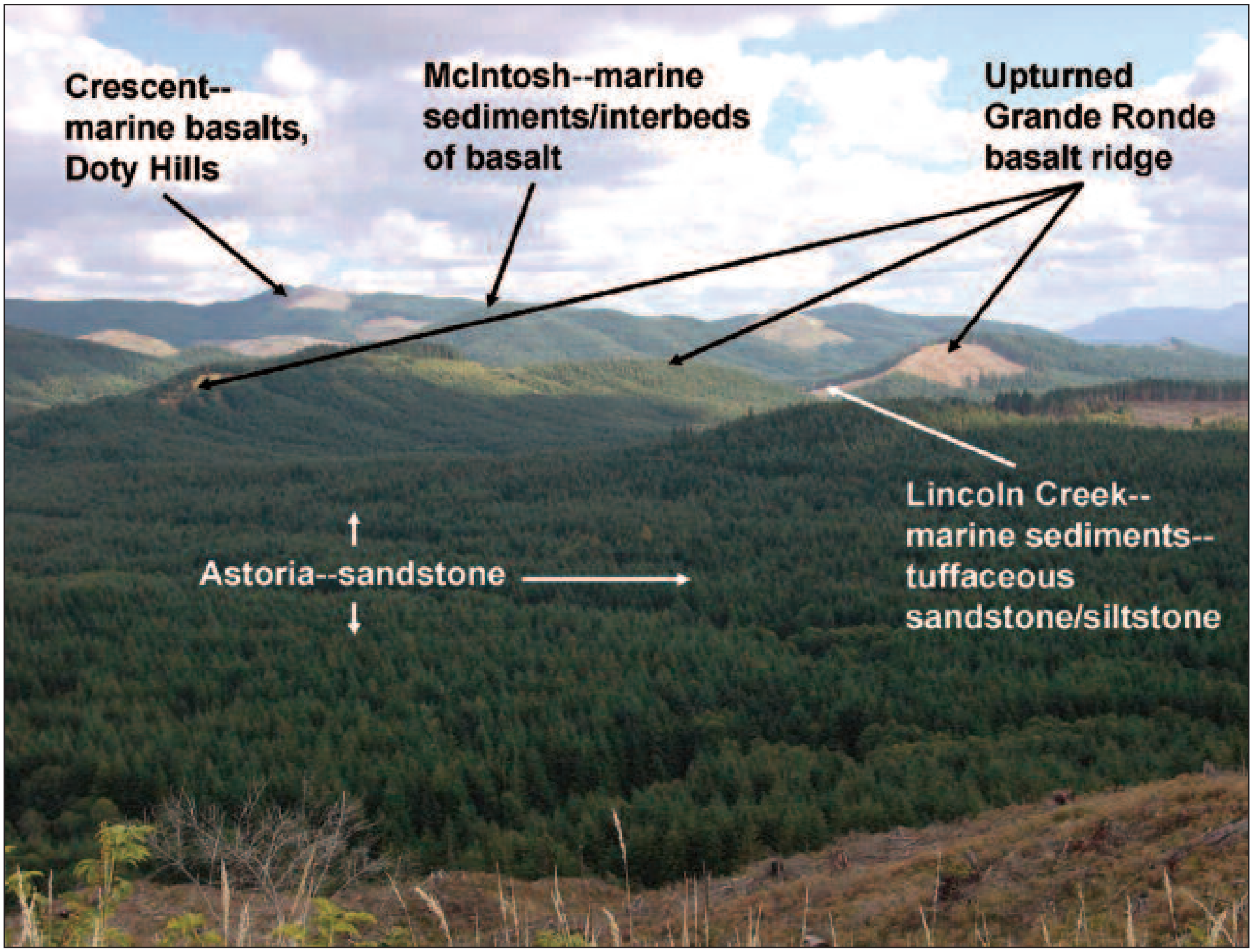

Figure 4—Geological formations around the Fall River research area in coastal Washington.

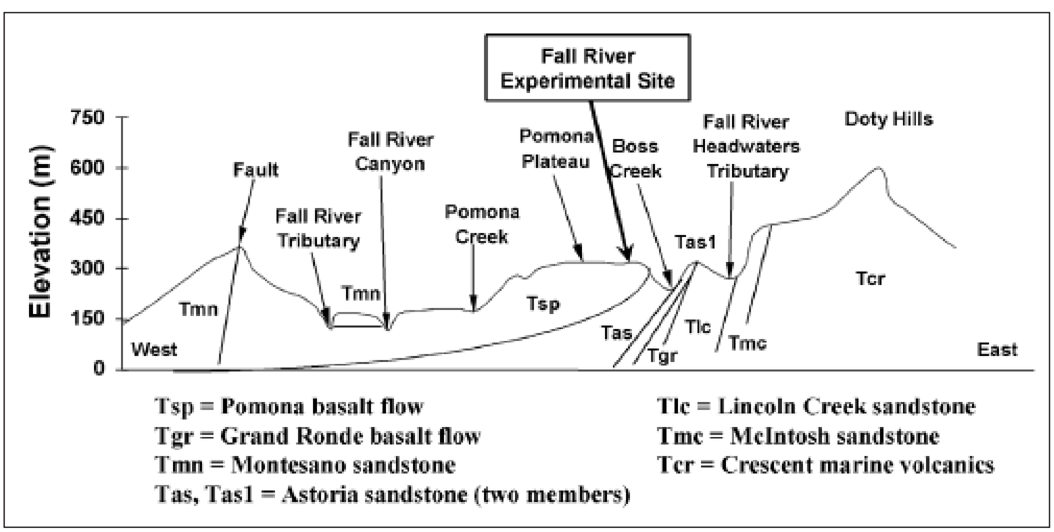

Figure 5—Geological profile in coastal Washington showing the location of the Fall River research area.

into Willapa Bay and Grays Harbor. Along the way, these basalt flows entered depositional basins containing semiconsolidated sediments. Instead of flowing along the surface, the so-called invasive flows tended to burrow into the sediments. The sedimentary sequences are deformed by faulting and folding. The Fall River research site is located on a plateau of the Pomona basalt flow (fig. 5), which is the longest lava flow in the world encompassing 600 km from its origin in west-central Idaho. Unlike the Olympic Mountains to the north, the rocks of the Willapa Hills are not intensely deformed because they were not subjected to subduction tectonism or the associated metamorphism. The subducting oceanic plate under the Willapa Hills extends deep under the Earth's crust.

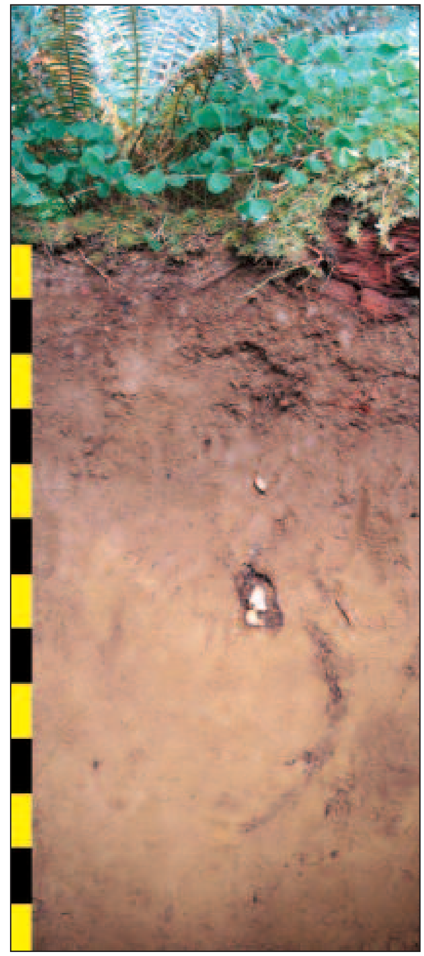

Figure 6—Typical soil profile of the Boistfort series at the Fall River research area. Every division of the measuring device is 10 cm.

Soils

The Boistfort soil has low bulk density, high organic matter content, and high water-holding capacity.

The soil at the Fall River study site has been classified as medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand (USDA NRCS 1999) of the Boistfort series developed from weathered Miocene basalt, and influenced by volcanic ash in the upper horizons (Steinbrenner and Gehrke 1973). Some of the volcanic ash is possibly from the eruption of Mount Mazama approximately 6,850 years ago. The modal sequence of horizons is A/AB/B/C (table 8). The Boistfort soil (fig. 6) is deep, well-drained, and mostly stone-free, and has low bulk density (BD), high organic C content, and high water-holding capacity (table 9).

To characterize local soil conditions with more detail, soil pits were excavated to about 1.5 m depth in August-September 2001 in the harvested buffer areas immediately adjacent to each of the four blocks of the experiment. Details of the experimental design are in "Treatments" section. Soil characteristics were similar in the four pits (table 10) except for greater organic C concentration (on a weight basis) in the A horizon of the pit adjacent to block 1. The C/N ratio was also greatest in that horizon suggesting a larger proportion of decomposing organic materials.

Table 8—Field description of the Boistfort soil at the Fall River experimental site in coastal Washington

Horizon	Depth	Description
	Centimeters	
O_i	1 - 0	Discontinuous coniferous litter consisting of needles, twigs, and branches, in some spots mixed into mineral soil (0 to 1.5 cm thick)
A	0 - 17	Dark brown (7.5 YR 3/3); silt loam; moderate, medium subangular blocky structure breaking to weak, fine to moderate, crumb structure; friable, slightly sticky, slightly plastic; common very fine, fine, medium and coarse roots; many fine and medium interstitial pores; some shot-like concretions evident; charcoal and fire-oxidized soil (5 YR 5/8) present; abrupt wavy boundary (12-17 cm thick)
AB	17 - 40	Dark brown (7.5 YR 3/4); silt loam; moderate, medium prismatic breaking to moderate fine/medium subangular blocky structure; friable, slightly sticky, slightly plastic; few very fine, fine, and common medium and coarse roots, many very fine and fine interstitial pores and common fine tubular pores; charcoal and fire-oxidized soil (5 YR 5/8) present; abrupt wavy boundary (19-24 cm thick)
$2B_w1$	40 - 85	Brown (7.5 YR 4/4); silty clay loam; moderate medium prismatic structure; firm, sticky, plastic; few very fine, fine, medium and coarse roots, common very fine interstitial and fine tubular pores; gradual smooth boundary (40-48 cm thick)
$2B_w2$	85 - 140+	Strong brown (7.5 YR 4/6); silty clay loam; moderate medium prismatic structure; firm, slightly sticky, slightly plastic; few very fine, fine, and medium roots, common very fine interstitial and few fine tubular pores; charcoal and fire-oxidized soil (5 YR 5/8) present

Note: Soil description by D. Zabowski, University of Washington, 1999.

Bulk density increased with depth, whereas total porosity and macropore volume had the opposite trend (table 9). Available water capacity (i.e., volumetric water content at -10 kPa minus that at -1500 kPa) at the 0- to 150-cm depth ranged from 33 to 37 cm, or 22 to 24 percent of total profile depth to 150-cm depth. Volumetric water content at -10 kPa (approximately field capacity) was much greater for the surface horizon than for subsurface horizons. Analysis of composite samples from the four blocks indicated a narrow range of both particle density (PD) measured by the pycnometer method, and particle-size distribution among the major horizons (table 11). As expected, PD was highest in the B horizon. The A horizon was a clay loam, and the other horizons were silty clay loam. Among-block differences appear largely related to spatial variation in organic matter rather than in soil texture or horizon thickness. These differences in organic matter likely induce variation in PD, volumetric soil water content at saturation, and soil water release curves. Blocking was also important to group plots along similar slope positions with blocks 1 and 2 on upper to mid slopes, and blocks 3 and 4 on lower slopes.

Mineralogical analysis of the clay fraction of the Boistfort soil by x-ray diffraction revealed the presence of hydroxyl aluminum-interlayered vermiculite and

Table 9—Soil physical characteristics at four sampling locations within the Fall River experimental area

Block	Depth	Horizon	Bulk density	Total porosity[a]	Volumetric water at tensions (Pa) of: 0	-10	-33[b]	-80	-200	-1500	Macropores[c] as percentage of: Core volume	Total porosity	AWC1[d]	AWC2[e]	AWC3[f]
	cm		*Mg/m³*	*Percent*											
1	0-17	A1	0.48	73.8	73.8	40.6	39.0	35.9	30.6	5.6	33.2	45.0	35.0	33.4	10.0
	17-40	AB	.80	73.0	73.0	50.6	49.1	46.1	42.5	13.6	22.4	30.7	37.0	35.5	8.1
	40-85	$2B_w1$	.90	64.4	64.4	42.0	40.9	38.8	36.9	16.2	22.4	34.8	25.8	24.7	5.1
	85-150+	$2B_w2$	1.14	58.2	58.2	45.8	45.0	43.5	43.6	30.4	12.4	21.3	15.4	14.6	2.2
2	0-12	A	.60	78.9	78.9	40.3	38.9	36.2	33.3	7.4	38.6	48.9	32.9	31.5	7.0
	12-50	AB	.70	72.7	72.7	42.3	40.8	37.8	35.8	9.8	30.4	41.8	32.5	31.0	6.5
	50-83	$2B_w1$	.92	60.4	60.4	36.2	35.5	34.0	32.3	18.2	24.2	40.1	18.0	17.3	3.9
	83-155+	$2B_w2$	1.12	58.0	58.0	45.1	44.5	43.2	36.8	25.0	13.8	23.8	20.1	19.5	8.3
3	0-18	A	.69	72.8	72.8	47.7	46.2	43.1	40.6	10.1	25.1	34.5	37.6	36.1	7.1
	18-46	AB	.72	69.4	69.4	42.1	40.8	38.2	36.2	11.0	27.3	39.3	31.1	29.8	5.9
	46-95	$2B_w1$	1.13	57.6	57.6	45.6	44.7	42.8	41.3	24.9	12.0	20.8	20.7	19.8	4.3
	95-155+	$2B_w2$	1.18	56.7	56.7	46.2	45.6	44.4	41.8	32.6	10.5	18.5	13.6	13.0	4.4
4	0-18	A	.60	73.2	73.2	39.8	38.2	35.1	32.7	7.7	33.4	45.6	32.1	30.5	7.1
	18-42	AB	.64	72.2	72.2	40.0	38.3	34.8	32.5	8.4	32.2	44.6	31.6	29.9	7.5
	42-90	$2B_w1$	1.02	60.9	60.9	40.6	39.6	37.7	36.1	21.7	20.3	33.3	18.9	17.9	4.5
	90-150+	$2B_w2$	1.10	58.7	58.7	44.7	44.1	42.9	41.3	27.8	14.0	23.8	16.9	16.3	3.4

[a] Total porosity estimated from measured bulk density in volumetric core samples in each horizon of the four pits and from particle density in every horizon from the four pits determined from a composite sample by horizon from the four pits (determinations made at Oregon State University Soils Laboratory).
[b] Based on linear interpolation between -10 and -80 kPa.
[c] Macropores = difference in volumetric moisture percentage between 0 kPa (saturation) and -10 kPa.
[d] AWC1 = volumetric water percentage at -10 kPa minus that at -1500 kPa.
[e] AWC2 = volumetric water percentage at -33 kPa minus that at -1500 kPa.
[f] AWC3 = volumetric water percentage at -10 kPa minus that at -200 kPa.

Table 10—Carbon, soil nutrients, and pH by horizon in four soil pits at the Fall River experimental area

Block	Depth	Horizon	C	N	P	K	Ca	Mg	C/N	pH
	cm		*% by weight*		- - - - - - - - *mg/kg* - - - - - - -					
1	0-17	A1	13.2	0.46	17.8	110	552	78.1	28.7	5.2
	17-40	AB	4.7	.26	7.3	83	56	10.7	18.2	5.2
	40-85	$2B_w1$	1.0	.07	2.8	70	80	19.9	13.6	5.2
	85-150+	$2B_w2$	.7	.05	2.9	51	120	66.7	13.6	5.1
2	0-12	A	7.4	.40	12.5	159	162	42.6	18.4	5.2
	12-50	AB	4.0	.24	6.4	41	13	4.0	16.5	5.1
	50-83	$2B_w1$	1.4	.09	2.9	86	65	16.7	15.9	5.0
	83-155+	$2B_w2$	.5	.04	3.7	37	89	75.8	11.8	5.0
3	0-18	A	9.1	.42	10.4	103	189	39.4	21.8	5.0
	18-46	AB	4.3	.24	5.2	35	22	6.6	17.9	5.1
	46-95	$2B_w1$	.7	.06	2.0	44	165	94.4	12.5	5.1
	95-155+	$2B_w2$	.5	.05	2.1	38	129	111.0	9.8	5.1
4	0-18	A	8.7	.39	9.5	73	71	23.0	22.3	4.8
	18-42	AB	4.4	.26	5.2	45	13	8.6	17.0	5.1
	42-90	$2B_w1$	.9	.09	2.2	45	37	24.2	9.4	4.9
	90-150+	$2B_w2$	.8	.07	2.1	39	60	68.4	11.1	5.0

Analyses were performed at the Pedology Laboratory, College of Agriculture and Life Sciences, University of Idaho, Moscow, ID.

Table 11—Soil particle density and size distribution in composite samples by horizon from four soil pits at the Fall River experimental area

Horizon	Particle density[a]	Gravel[b]	Sand	Silt	Clay	Textural class
	g/cm³	- - - - - - - - - *Percent* - - - - - - - - - -				
A	2.36	3.6	29.0	35.0	32.3	Clay loam
AB	2.67	2.0	12.2	46.0	39.9	Silty clay loam
$2B_w1$	2.77	2.5	11.2	46.9	39.3	Silty clay loam
$2B_w2$	2.79	3.0	11.3	46.1	39.7	Silty clay loam

[a] Determined by the pycnometer method at the Pedology Laboratory, College of Agriculture and Life Sciences, University of Idaho, Moscow, ID.

Textural fractions were determined at the Soil Laboratory, College of Forest Resources, University of Washington.

[b] Coarse fragments between 2 and 75 mm in diameter.

some kaolin. The hydroxyl-interlayered vermiculite has properties that are intermediate between those of vermiculite (a 2:1 clay) and chlorite (a 2:1:1 clay). The interlayering is extensive enough to prevent complete collapse of the mineral upon saturation with potassium (K) and heating (as with vermiculite) but not extensive enough to maintain the 14-Å spacing when heated (as with chlorite).[3] Selective dissolutions of iron, aluminum, and silica in Fall River soil samples showed that allophane and imogolite concentrations were low compared to other Andisols, and increased slightly with soil depth.[4]

Preharvest Forest Stand Characteristics

Stand History

The original old-growth Douglas-fir/western hemlock stand was harvested in 1952-53 by cable yarding. The clearcut area was broadcast burned in 1953 and planted in winter 1953-54 with 2+0 Douglas-fir seedlings at 2,188 trees per ha. Naturally regenerated western hemlock also became a significant component of the plantation. In 1971, the stand was precommercially thinned from 2,235 to 1,220 trees per ha. The stand was fertilized four times with urea in 1970 (370 kg N/ha), 1979 and 1984 (493 kg N/ha in each year), and 1995 (448 kg N/ha). The Fall River site has a site index of 41 to 43 m at breast-height age 50 years that corresponds to a site class of II+ to I (King 1966). Before harvest in 1999, there was no evidence of significant compaction or disturbance within the stand. Any area with obvious yarding-related disturbance was dropped from the study. A view of the preharvest stand is presented in figure 7.

Stand Description

Methods—

Before the installation of the treatments, all 48 study plots within the 47-year-old stand planted in 1953-54 were assessed to determine overstory and understory vegetation composition, and biomass and wood volume in live and dead trees. Frequency of live and dead trees and snags, bole diameter, total tree height, and species compositions were recorded in the 0.1-ha internal measurement plot. Bole diameter at breast height (d.b.h.; 1.3 m above ground) was measured for all trees, and height was measured for 1,440 trees (30 trees per plot) across the d.b.h. range within each plot. Snags were rated following a five-stage system (Neitro et al. 1985) in which a stage-1 snag is a recently dead tree with an intact top. Data were summarized by species and survivor code (live or dead tree). Volume of each tree was calculated based on d.b.h. and actual or estimated height. Coefficients of

[3] Fallen, A.L. 2005. Personal communication. Research associate, University of Idaho.
[4] Strahm, B.D. 2006. Personal observation. Doctoral candidate, University of Washington.

Figure 7—View of the preharvest forest stand at the Fall River research area.

Table 12—Stand density, mean tree size, stand basal area, and wood volume for live Douglas-fir and western hemlock trees in the stand before harvest at Fall River

	Stand density	Mean diameter[a]	Mean height	Basal area	Total wood volume
	Trees/ha	*cm*	*m*	m^2/ha	m^3/ha
Douglas-fir	303	38.0	32.9	37.6	500
Western hemlock	324	33.3	30.2	32.5	414
Total	627			70.1	914

[a] Diameter measured at breast height, 1.3 m.

height-diameter relationships and estimated height for each tree were determined in Proc NLIN (SAS Institute 1999). Separate volume equations were used for Douglas-fir (Bruce and De Mars 1974) and western hemlock (Wiley 1975).

Height and d.b.h. of all partially decomposed snags (stage 2 through 5) within the internal measurement plots were also recorded. Total height of snags was measured to the broken top, and the equation developed by Bruce and De Mars (1974) was used to estimate the standing volume of the snag.

Results—

Forty-eight percent of the trees in the stand were Douglas-fir and contributed approximately 55 percent of the total stand volume (table 12). Total basal area was 70 m^2/ha, reflecting both the high stand density and site index. Mean d.b.h. and total tree height were 14 percent and 9 percent greater, respectively, in Douglas-fir than in western hemlock.

Biomass and C and N Stores

Forest Stand—

Methods

Tree diameters at 1.3 m above ground were measured in spring 1998 on 7,532 trees within the study area with a diameter tape. Total height was measured with a Vertex II laser device (Haglof, Inc.) on a subset of 30 trees within each of the 48 treatment plots, including trees with the smallest and largest d.b.h. Height-diameter curves based on the sample trees were developed for each species and used to estimate heights for all trees in the stand. A stand table of d.b.h. and total heights was generated for all stems within the treatment area.

Local above-ground biomass equations were developed for Douglas-fir and western hemlock.

To select trees for biomass sampling, the stand d.b.h. and height data were divided into five diameter and total-height classes, and the percentage of basal area in each diameter class was calculated. The number of trees selected within each diameter class was based on the proportion of basal area represented within that diameter class for each species. When an even number of trees were required for a given diameter class, half of the trees were selected from the top half of the height distribution within the class and half from the bottom half of the height frequency distribution. When an odd number was required, the remaining tree was selected from across the entire height distribution within a class. A total of 31 Douglas-fir trees ranging in d.b.h. from 15.0 to 80.1 cm and 24 to 40 m in height, and 11 western hemlock trees ranging in d.b.h. from 20.0 to 61.7 cm and 27 to 37 m in height were selected for detailed characterization. The original plan was to select approximately 30 trees of each species, but time and budget constraints resulted in fewer hemlock trees being sampled.

Each tree was inspected to make sure that it had no obvious abnormalities such as forked, crooked, or hollow stems, or damaged crowns. If abnormalities were found, another tree was randomly selected from the appropriate class. A plastic tarp was placed on the ground so that the full tree when cut would land on the tarp. Stump heights, felled-tree heights, and height-to-live-crown were measured from the uphill side of the tree. Dead branches were removed, collected, and weighed, and representative subsamples were taken up the bole for fresh and dry-weight determinations. All subsampled biomass material was placed in plastic bags and later oven-dried at 65 °C to constant weight at the Laboratory of the College of Forest Resources, University of Washington. Dry biomass was estimated by multiplying the original biomass by a factor that adjusted for moisture loss.

Live branches were removed and weighed. A representative subsample was taken along the live crown. Branches were placed in plastic bags and later dried to constant weight at 65 °C. After oven-drying, needles were removed and the ratio of needles to live branches was used to calculate total dry live branches and foliage weights. Any small, broken log sections and all tree top sections above 5 cm diameter were measured and weighed in the field. A 10-cm-thick disk was taken from the middle of each broken log segment and from the top section above 5-cm diameter for a density determination pertaining to that particular log section.

Outside-bark diameters of Douglas-fir logs were measured at 61-cm intervals along the length of each log. Stems were then cut into eight equal-length log sections and outside-bark diameters were measured at the small- and large-end diameter of each log section. Outside-bark diameters of western hemlock logs were only measured at the small- and large-end diameter of each of the eight log sections. Five-cm-thick wood disks were cut from the midpoint of each log section, weighed, and transported to the laboratory of the College of Forest Resources, University of Washington for detailed measurements and oven drying. For each disk, two inside-bark diameter measurements were taken at right angles to each other on both sides of the disk and then averaged. The average bark thickness to 0.5 mm was measured from four locations equally spaced around the wood disk circumference. Disk thickness was measured with calipers every 60°, and disk volume was estimated as a cylinder. Disks were oven-dried at 65 °C until constant weight, and bole bark and bolewood were separated and weighed. The dry-weight density for the green volume of each disk was used to calculate the dry weight of bolewood and bark for each respective log section.

Outside bark volumes (wet) of the eight log sections per tree were calculated based on the diameter measurements recorded in the field for each respective log section. Volumes were calculated for each 61-cm length section along the eight Douglas-fir log bolts per tree, whereas for western hemlock, volumes were calculated for each of the eight log bolts. Volume for each measured log section was calculated according to the two-end conic formula:

$$V = [1/3 \ \text{length} \ ((A1+A2+(A1A2)^{0.5}) \ ] \ 0.000001 \qquad [1]$$

where V = outside bark log volume (m^3) for the log section, length = log-section length (cm), $A1$ = area (cm^2) of large end of log section, and $A2$ = area (cm^2) of small end of log section.

For each log section, bolewood biomass (kg) was calculated by first multiplying the log section wet volume by the percentage of bolewood volume from the corresponding disk section, then by bolewood density. The same procedure was used to calculate bark biomass.

Stump volume was estimated with the sub-neiloid formula (Briggs 1994):

$$V = 0.00007854\ ((d + D)/2)^2\ \text{stump height} \qquad [2]$$

Where V = volume (m^3), d = stump top diameter outside bark (cm), and D = ground-line diameter outside bark measured at the top of apparent basal lateral root protrusions (cm). The wood density of the first log-section disk was used for the density of the stump-volume section.

Total stem biomass was then calculated by summing the biomass of bolewood and bark for each log section and then adding stump biomass and any broken top biomass for each tree.

Biomass equations were developed for bole wood, bole bark, dead branches, live branches, and foliage as:

$$Y = \text{a}\ DBH^{\text{b}} \qquad [3]$$

where

Y = component biomass (kg), DBH = outside-bark diameter at 1.3 m height (cm), and a and b = equation coefficients. The equations were transformed to natural logarithms to be fitted by linear regression.

Carbon and N concentrations were determined in samples of bark, bole wood, live branches, dead branches, and foliage for a subset of biomass trees. Samples were from one tree in each of the d.b.h. classes with the exception of d.b.h. classes 45.1-50.0 cm, and 50.1-55.0 cm, which had samples from two trees because of the high tree frequency and basal area in these classes. All sample lots were made by proportionately sampling the component up and down the tree based on either biomass or volume within the section sampled. Ground and oven-dried samples were thoroughly mixed, and subsamples were ground again in a Wiley mill to pass a 60-mesh sieve, oven-dried at 65 °C, grouped by component type, and stored in airtight bags until analysis. Carbon and N concentrations were analyzed by following the dry combustion method with a CHN 2400 analyzer (Perkin Elmer Corp.) at the Laboratory of the College of Forest Resources, University of Washington. In addition, upon completion of the analyses, C and N concentrations for each component of Douglas-fir were regressed against tree d.b.h. No correlations were found between concentration and diameter, so an average C and N concentration was calculated for each biomass component.

Table 13—Coefficients of biomass equations developed for Douglas-fir and western hemlock at Fall River

Tree component	Equation coefficients b_1	b_2	r^2
Douglas-fir:			
Foliage	-6.5110	2.4826	0.86
Live branches	-6.0845	2.7364	.91
Dead branches	-4.9085	2.2536	.81
Bole wood	-.9388	1.9941	.94
Bole bark	-3.9923	2.2250	.97
Total aboveground biomass	-.9950	2.0765	.99
Western hemlock:			
Foliage	-3.3835	1.7563	.83
Live branches	-3.3125	1.9622	.77
Dead branches	-5.4125	2.2290	.94
Bole wood	-2.0149	2.2641	.95
Bole bark	-5.2355	2.5040	.92
Total aboveground biomass	-1.6612	2.2321	.96

Note: Equations are of the form: ln(biomass [total or component in kg]) = $b_1 + b_2$ ln(d.b.h. [in cm]). Range in d.b.h. was 15.0 to 80.1 cm for Douglas-fir and 20.0 to 61.7 cm for western hemlock.

Table 14—Carbon and nitrogen concentrations in aboveground tree biomass components in Douglas-fir and western hemlock at Fall River

Tree component	Douglas-fir C	Douglas-fir N	Western hemlock C	Western hemlock N
	Percent			
Bole wood	48.8 (0.16)	0.08 (0.01)	48.3 (0.05)	0.07 (0.01)
Live branches	49.7 (.12)	.26 (.04)	48.8 (.07)	.15 (.03)
Dead branches	48.5 (.09)	.20 (.04)	49.4 (.06)	.08 (.02)
Bark	51.9 (.32)	.40 (.05)	50.1 (.77)	.35 (.02)
Foliage	53.1 (.20)	2.02 (.07)	51.7 (.14)	1.43 (.05)

Values are means with one standard error in parentheses (n = 15 samples for Douglas-fir and 12 samples for western hemlock, except for live branches in Douglas-fir where n = 14).

Results

Regression equations fit the data well for tree biomass components for both Douglas-fir and western-hemlock (table 13). Explained variance ranged between 77 and 99 percent. Equations for bole wood and total biomass for both species had higher r^2 (0.94 to 0.99) than equations for branches and foliage (0.77 and 0.94).

Average C concentrations ranged from 48.8 percent in bole wood to 53.1 percent in foliage in Douglas-fir, and from 48.3 percent in bole wood to 51.7 percent in foliage in western hemlock (table 14). Foliage N concentration was markedly

Table 15—Biomass and carbon and nitrogen stores in the pre-harvest Douglas-fir/western hemlock stand at Fall River

	Biomass		Carbon		Nitrogen	
Tree component	*Mg/ha*	*%*	*Mg/ha*	*%*	*kg/ha*	*%*
Douglas-fir:						
Foliage	4.4	1.9	2.3	2.0	88.7	23.6
Live branches	17.8	7.6	8.8	7.6	45.7	12.2
Dead branches	9.2	3.9	4.5	3.9	18.0	4.8
Bole wood	182.2	77.8	88.9	77.2	140.3	37.3
Bole bark	20.6	8.8	10.7	9.3	83.2	22.1
Total aboveground	234.2		115.2		375.9	
Western hemlock:						
Foliage	5.1	3.2	2.6	3.3	73.0	31.9
Live branches	11.5	7.3	5.6	7.2	17.2	7.5
Dead branches	3.7	2.3	1.8	2.3	2.9	1.3
Bole wood	126.2	79.6	61.0	78.6	93.4	40.9
Bole bark	12.1	7.6	6.7	8.6	42.1	18.4
Total aboveground	158.6		77.7		228.6	
Stand total:						
Foliage	9.5	2.4	4.9	2.5	161.7	26.8
Live branches	29.3	7.5	14.4	7.5	62.9	10.4
Dead branches	12.9	3.3	6.3	3.3	20.9	3.4
Bole wood	308.4	78.5	149.9	77.7	233.7	38.7
Bole bark	32.7	8.3	17.4	9.0	125.3	20.7
Total aboveground	392.8		192.9		604.5	

greater in Douglas-fir (2.0 percent) than in western hemlock (1.4 percent). Douglas-fir also had markedly higher N concentrations in live and dead branches than western hemlock.

The aboveground portions of the trees in the 47-year-old stand contained 193 Mg/ha of C and 604 kg/ha of N.

The aboveground portions of the trees in the 47-year-old stand contained 193 Mg/ha of C and 604 kg/ha of N (table 15). Douglas-fir and western hemlock had similar relative proportions of aboveground C in boles (77 percent and 78 percent, respectively), but western hemlock had proportionately more C and N partitioned to foliage (3 percent versus 2 percent for C, and 32 percent versus 24 percent for N).

Total aboveground biomass in bole, bark, branches, and foliage was 393 Mg/ha (table 15). That value was markedly greater than biomass estimates for eight 22- to 52-year-old stands in the Pacific Northwest (table 16). Older stands (90 to 110 years old), however, had more than 60 percent greater total aboveground biomass than the stand at Fall River.

Understory vegetation biomass—

Methods

We collected aboveground biomass of understory vegetation from five subplots within each treatment plot. To systematically locate each subplot, the longest side

Table 16—Estimates of component and tree biomass in stands ranging in age between 22 and 110 years in the Pacific Northwest

Source	Stand age	Condition	Stand density	Bole wood	Bole bark	Branches		Foliage	Total above-ground
						Live	Dead		
	Years		*Trees/ha*	- - - - - -	- - - - - -	- - - - *Mg/ha*	- - - - - -	- - - - - -	- - - - - -
Bancalari and Perry (1987)	22	Slow growth	1030	62.4	11.7	15.7[a]		8.9	98.7
		Medium growth	770	100.5	16.9	20.6[a]		10.7	148.7
		Fast growth	690	140.7	25.6	22.9[a]		14.5	203.7
Dice (1970)	36		2223	134.4	18.5	5.5	5.7	7.8	176.1[b]
Swank (1960)	37		1370	121.2	20.4	17.6	6.8	11.1	177.1
Heilman (1961)	38		6125	51.6	18.1	8.5	10.1	8.0	96.3
	38	N-fertilized	4940	63.8	21.4	17.0	13.3	14.2	129.7
Barclay et al. (1986)	43		NA	100.4	17.0	13.1	7.2	11.7	151.1[b]
Heilman (1961)	52		6125	147.4	27.2	17.9	11.2	11.9	215.6
	52	N-fertilized	5335	142.4	30.8	21.2	9.0	13.8	217.2
Fujimori et al. (1976)[c]	90-110		478	510.2	69.2	46.3[a]		10.5	636.2

[a] Dead branches included in estimates of live branches.
[b] Sums as reported in publication.
[c] Stands with Douglas-fir and western hemlock.

of the plot was divided into five equal lengths of 17 m each (0-17, >17-34, >34-51, >51-68, and >68-85 m), and one 2-m radius circular plot was randomly located within each of the five rectangles (17 by 30 m) based on x, y coordinates from the NE plot corner.[5] If the sample point was on a log, stump, or a tree location, it was moved 1 m in a random direction (0 to 360° bearing). If the sample point was also a soil sampling point, it was moved away from large stump roots at 1-m increments in a random direction until clear of obstructions.

Oxalis occurred as an extensive plant cover and was sampled separately from other understory plant species. At each of the five subplots per plot, a 0.25-m^2 metal square was placed on the ground. All aboveground oxalis, including roots in the litter, but not in the mineral soil, were manually removed and put into labeled plastic bags. Samples of other plant species were collected within 2-m-radius circular areas (12.6-m^2) centered at each of the five sample points. Aboveground biomass of all understory vegetation that originated in the subplot was clipped with hand shears at ground line, collected in paper bags, and oven-dried at 65 °C in the laboratory to constant weight. Concentrations of total C and N of the samples (48 samples for oxalis, and 48 samples for other vegetation) were determined by the dry combustion method at the University of Washington Analytical Services Laboratory.

Results

Understory vegetation included forbs, ferns, and shrubs. Collectively, stores of biomass, C, and N in understory vegetation were small (< 95 kg/ha of C, and < 5 kg/ha of N; table 17), and a very small proportion of the C and N stores at the site. Given its high foliage N concentration (2.8 percent) and extensive plant cover, oxalis with 3.3 kg N/ha contributed 67 percent of the understory N store.

Forest floor, coarse woody debris, and old-growth stumps and snags—

Methods

The primary objective of sampling forest floor, woody debris, and old-growth stumps was to obtain good estimates of those components by block rather than by plot. We defined coarse woody debris (CWD) as detrital wood from 5 to 60 cm diameter (in the preharvest sampling) and later as 0.6 to 60 cm diameter (in the postharvest sampling). Biomass, C, and N stores in old-growth logs, old-growth

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[5] The same quintile subplots were used to facilitate other sampling protocols as well. Sampling locations were randomly assigned to quintile subplots without replacement so that samples would be distributed uniformly across the treatment plots.

Table 17—Average biomass and carbon and nitrogen concentrations and stores in understory vegetation before forest harvest at Fall River

	Biomass	C	N	C	N
	kg/ha	- - - - - - - *Percent* - - - - -		- - - - - - - *kg/ha* - - - - - -	
Understory vegetation (except oxalis)	102.3 (6.8)	48.2 (0.36)	1.8 (0.15)	42.7 (3.0)	1.6 (0.4)
Oxalis	118.2 (30.0)	43.7 (.70)	3.0 (.20)	52.1 (12.0)	3.3 (.7)
Total understory vegetation	220.5			94.8	4.9

Values are means with one standard error in parentheses (n = 45 and 47 samples for understory vegetation and oxalis, respectively).

stumps, and snags were reported separately from CWD although, strictly, they are woody debris of coarse size.

From each of two randomly chosen subplots within each study plot, one forest floor sample was collected in summer 1998. Sample points within a subplot were determined by randomly picked x, y coordinates. Samples of the forest floor material were then collected within a 0.25-m^2 square frame. The frame was offset to the nearest acceptable sampling point if the point landed on a log, stump, or clump of vine maple. The forest floor sample included limbs and woody debris less than 5 cm in diameter that could be cut with shears, moss, litter, partially decomposed organic material, and rot down to the mineral soil. Obvious roots in the forest floor were discarded. Amorphous (i.e., lacking the integrity of an intact log) material in woody debris decay classes 4 and 5 was included in the forest floor samples. A small garden scoop was used to excavate red rot material down to the mineral soil. The forest floor components were not separated. The entire sample was placed in a labeled plastic bag and stored in cold storage until oven-drying at 70 °C and subsequent weighing. Dry weights of the two forest floor biomass samples per plot were averaged, and then biomass per hectare was computed.

Coarse woody debris > 5 cm in diameter from the 47-year-old stand (excluding large old-growth logs, stumps, and snags) was assessed from September to December 1998. Each treatment plot, which includes the internal measurement plot and the treatment buffer, was first divided into five equal sections (quintiles). A 30-cm-wide by 15-m-long transect was randomly located within each of three quintile subplots within each plot. Transect lengths were not adjusted for slope because the slopes were gentle and relatively short. Sampling was without replacement so that no subplot would have more than one transect. Starting points for transects were chosen based on random x, y coordinates within the subplot. The transect line was then oriented in a randomly chosen bearing direction from 1° to 360°. If a transect

Table 18—Description of decay classes (Maser et al. 1979) used in the pre- and postharvest assessments of coarse woody debris, old-growth logs, and old-growth stumps at Fall River

Class	Description
1	Fresh logs with foliage, bark, and small limbs intact. These logs were generally western hemlock with Annosus root rot blown down within the stand. No Douglas-fir root-rot disease mortality was observed on the site.
2	Logs with bark sloughing, some limbs present, foliage not evident, and wood discolored but firm.
3	Logs with trace of bark, limbs absent, wood texture firm in the center, and center wood faded/stained. Outside of the log may display blocky brown cubicle rot, for instance, in large remnant old-growth logs.
4	Logs with bark absent, texture soft to firm, and with mostly blocky brown cubical rot. Logs may have very small portion of class 3 in the heart of the log.
5	Logs with bark and twigs absent, considerable amount of moss present, soft-granular texture, textured, and brown decomposed wood as part of the forest floor.

would have extended off the treatment plot, it was directed back into the plot by following the reverse bearing. In a few cases, transects were located near a plot corner so that the entire transect could not be located within the plot. In these situations, an additional transect was placed within the same plot by using similar location procedures such that the total length of the two transects was equal to 15 m. Any CWD crossed by a transect was categorized by cross-sectional diameter and decay class (table 18). Debris materials that could be weighed directly were weighed in the field. Because rainfall would affect CWD wet weights, a subsample of logs within each decay class was collected daily to develop a dry-weight adjustment for that class of material based on the moisture content for the specific survey period. Large logs that could not be efficiently weighed in the field were sampled by the following method: a 30-cm-wide cross-section sample was collected and the weights subsequently adjusted to reflect the actual volume of the material that was intersected by the transect. Log measurements needed for the intersected log volume calculation are demonstrated in figure 8. Biomass was then calculated by multiplying the sample volume by the corresponding wood density determined for each decay class. This method was only used for larger logs up to 60 cm in diameter. Larger old-growth logs were assessed during the more intensive postharvest survey described in the section “Postharvest Biomass and C and N Stores.”

From 6 to 15 random subsamples of each woody debris decay class were taken from samples collected for moisture determination and underwent C and N analysis at the Analytical Services Laboratory of the College of Forest Resources, University of Washington, as previously described. A subset of samples was also

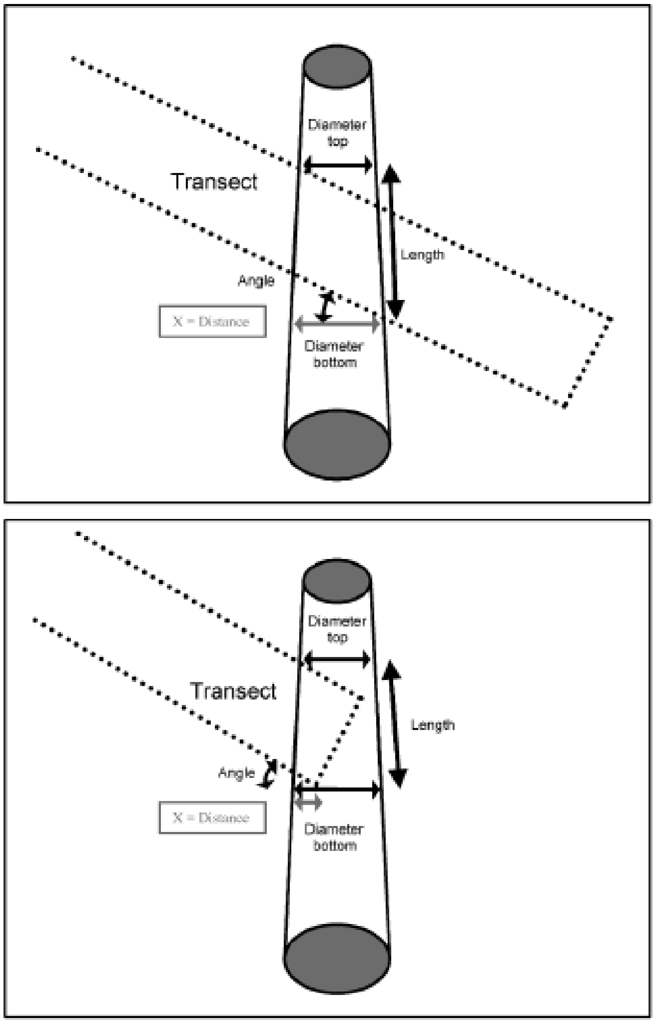

Figure 8—Measures taken to determine volume of logs in transects at the Fall River research area. Examples are for situations when the transect crosses over the log (top) or ends on the log (bottom).

analyzed by using the same methods at the Weyerhaeuser Analytical Laboratory, Federal Way, Washington, for cross-checking. These C and N concentrations were used to calculate C and N stores in CWD in the preharvest assessment survey.

Frequency and volume of old-growth stumps and snags were estimated in April 2002 to February 2004 after harvest and treatment installation. When a stump or snag was located, the closest tagged tree number was recorded for reference, and then the stump or snag height, diameter, and decay class were recorded. Tree species was identified based on bark characteristics, if feasible. Stumps and snags of unidentifiable species were recorded as “unknown conifer species,” as any hardwoods present in the old-growth stand would have decayed beyond recognition as a snag or stump. The standard five-class decay system (Maser et al. 1979) was used to characterize decay class; however, only codes 3, 4, and 5 were used because stumps and snags were from trees that had died at least 50 years before the survey. Many stumps and snags were more decayed on the exterior than in the center. To better represent these situations, intermediate codes of 3.5 (equal amounts of class 3 and 4 present), 3.8 (mostly class 4 but some class 3 material still visible), and 4.5 (equal amounts of class 4 and class 5 material) were also used. Stump and snag heights were measured with a tape for short individuals, and with an Impulse instrument (Laser Technology) for tall individuals. Because height measurements were to be used in volume calculations, a mean height to the top of the full cross section of a stump or a snag was recorded rather than the maximum height for a portion of the individual. Diameter for short stumps and snags was determined by measuring across the top (usually two values were measured and the average recorded). For taller individuals, diameter was measured with a diameter tape around the outside of the individual. Both basal diameter taken approximately at ground line, and a high diameter were measured. Height of the "high diameter" measurement was recorded. The high diameter was the diameter at the tallest height that represented the mass of the stump or snag and was reachable from the ground. To account for the substantial loss of material in the center of some stumps and snags, the approximate diameter of a hollow center area was also recorded and substracted. Each individual was also assigned a shape code (cylindrical, conical, or amorphous) to aid in estimating volume. Carbon and N stores were calculated by multiplying biomass by C and N concentrations for the corresponding old-growth log decay classes as described in sections to follow "Old-growth legacy wood" and "Stumps." We interpolated concentration values when classes were described as intermediate between defined classes (e.g., class 3.5).

Results

Under the Douglas-fir/western hemlock stand prior to harvest, the forest floor accounted for 71 Mg/ha. Carbon concentration in the forest floor averaged 37 percent, and N concentration averaged 0.9 percent. Stores of C and N in the forest floor amounted to 27 ± 4 (standard error) Mg/ha and 453 ± 51 (standard error) kg/ha, respectively. Coarse woody debris, excluding old-growth logs, stumps, and snags, in the Douglas-fir/western hemlock stand averaged 22 Mg/ha with 72 percent of this amount in decay classes 3 and 4 (table 19). Carbon concentrations were approximately similar for all CWD decay classes ranging from 47 percent for class 2 to 51 percent for class 4 (fig. 9). Nitrogen concentrations, however, differed

Table 19—Biomass and carbon and nitrogen stores in coarse woody debris by decay class before harvest at Fall River

Decay class	Biomass	Carbon	Nitrogen
	- - - - - -*Mg/ha*	- - - - -	*kg/ha*
1	2.2 (0.8)	1.0 (0.4)	1.4 (0.5)
2	2.8 (.4)	1.3 (.2)	5.1 (.9)
3	7.9 (1.2)	3.9 (.7)	24.8 (4.3)
4	8.2 (1.1)	4.1 (.5)	36.9 (4.8)
5	1.2 (.5)	.6 (.3)	6.1 (2.9)
Total	22.3	10.9	74.3

Values are means with one standard error in parentheses (n = 48 plots).

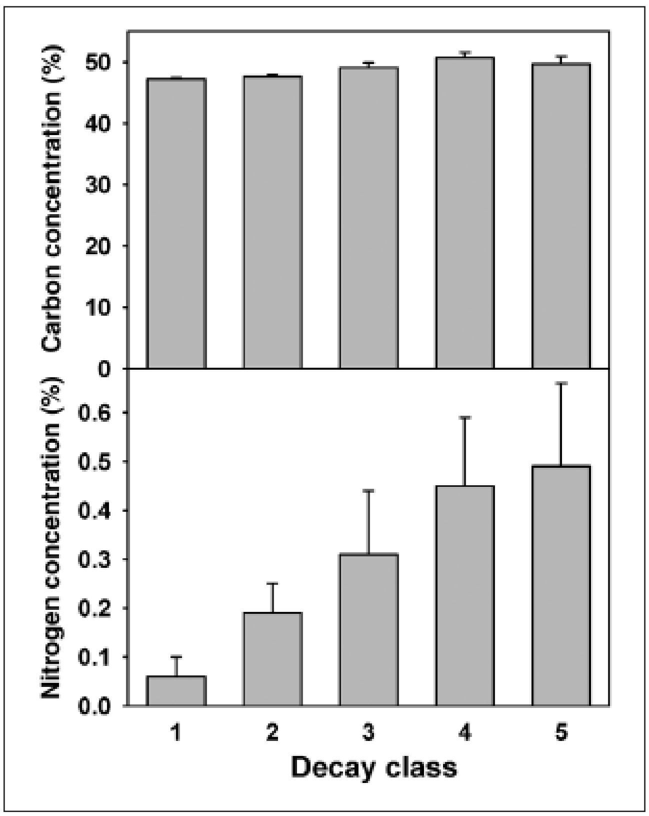

Figure 9—Carbon and nitrogen concentrations in coarse woody debris by decay class at the Fall River research area. Values are means ± one standard error.

Table 20—Density, biomass, and carbon and nitrogen stores in old-growth stumps and snags at Fall River

Species	Density	Biomass	Carbon	Nitrogen
	No. per ha	*Mg/ha*	*Mg/ha*	*kg/ha*
Douglas-fir	23.5 (3.9)	25.4 (4.5)	15.2 (2.2)	21.3 (4.2)
Western hemlock	8.4 (2.0)	2.8 (.5)	1.4 (.5)	2.9 (1.2)
Unknown	5.2 (1.3)	1.3 (.6)	0.7 (.3)	1.4 (0.6)
Total	37.1	29.5	17.3	25.6

Values are means with one standard error in parentheses (n = 48 samples).

There were 12.2 legacy stumps and snags per hectare.

markedly among decay classes (e.g., 0.06 percent for class 2 to 0.49 percent for class 5). There was less C and N stored in CWD (11 Mg/ha and 74 kg/ha, respectively) than in the forest floor (27 Mg/ha and 453 kg/ha, respectively).

The survey identified 443 legacy stumps and 19 legacy snags in 48 plots, a total survey area of 12.2 ha. Legacy stumps and snags amounted to 37 per ha with a total biomass of 29 Mg/ha (table 20), containing 17 Mg C/ha and 26 kg N/ha. Douglas-fir was the most common species identified (64 percent), followed by western hemlock (22 percent) and 14 percent unknown conifer species. One individual was classified as Sitka spruce. Over half (55 percent) of the individuals were classified as decay class 3.5 or 3.8, 22 percent as class 4, and the remaining individuals as classes 3, 4.5, or 5. Heights of the individuals ranged from 0.1 to 16.5 m with a mean of 1.4 m. In addition to one very tall snag (16.5 m), there were 11 snags and 1 stump between 3 and 7 m; the rest were less than 3 m tall. Basal diameters ranged from 20 to 430 cm with a mean of 188 cm. Individuals were distributed by basal diameter class as follows: 4 > 400 cm, 33 between 300 and 400 cm, 165 between 200 and 300 cm, 194 between 100 and 200, and 66 < 100 cm.

Soil—

Methods

Because of the size of the study, preharvest assessment of soil properties across the study area was undertaken to generally describe the preharvest soil properties within blocks, rather than to perform a detailed assessment at the plot level. We first sampled soils in summer 1998 by using a 31.2-mm diameter punch-tube volumetric sampler (Clements Associates) after collecting forest floor material. This soil sampling was independent of the sampling in four soil pits used to characterize the soil in the study area. From a 0.25-m^2 area at two random locations in each plot, two soil cores were taken by depth (0-10 cm, 11-30 cm, 31-50 cm, and 51-80 cm). Sample integrity was maintained for bulk density determination. Sample depth for each of the two separate cores was recorded, along with an estimate of A-horizon compression caused by the probe. For the preharvest sampling, 384 soil samples were collected (48 plots x 2 samples per plot x 4 depths). To test for possible differences between this method and procedures using larger core samplers, nine paired samples were also taken from the A horizon by using the small soil core sampler and a 137-cm^3 hammer-driven sampler (a cylinder with 5.4-cm diameter and 6-cm length). A small-diameter soil probe may compact the soil and render inaccurate bulk density values if the sampler edge is not sharp, sampling pressure is not applied correctly, and sampling depth is not monitored carefully. Our results, however, indicated that mean bulk density did not differ between the two sampling methods (P = 0.65).

Total N in the mineral soil and roots was more than 10-fold the N store above the mineral soil.

Soil samples were taken to the Laboratory of the College of Forest Resources, University of Washington and air-dried to constant weight. Soil bulk density (g/cm^3) was calculated as total oven-dry weight divided by the soil volume calculated from the soil sampler dimensions. After drying, the two samples from each plot were composited to produce a single sample for each depth per plot for determinations of pH (1:2 soil-water ratio), moisture content, percentage coarse fraction (> 2 mm), C, N, and other elements. For water content determinations, a field sample was weighed; then, 10 to 20 g of air-dried soil was oven-dried at 105 °C for 24 to 48 hours to estimate total oven-dried weight. Soil nutrient analyses were performed on the < 2 mm fraction. Content of larger fractions (mostly roots) was < 5 percent of bulk volume. A representative subsample was selected and ground to powder in a mortar and pestle. Samples were stored in plastic bags until C, N, and acid digest/inductively coupled plasma spectrometry analyses for total elements were performed (Kalra and Maynard 1991). Element contents per ha (*Q*) were calculated from element concentration as:

$$Q \text{ (kg/ha)} = \text{Depth (cm)} \times \text{bulk density (g/cm}^3) \times \text{concentration} \times 10^8 \text{ cm}^2/\text{ha} \times 0.001 \text{ kg/g}. \quad [3]$$

Results over all depths were summed to estimate a total nutrient pool estimate per hectare.

Results

Observations from the four pits indicated that C concentration within the soil profile followed an irregular distribution with lower C values in the 12.3- to 23.3-cm sampling depth (mostly in the AB horizon) than in the sample depths immediately above and below this depth (table 21). The upper 42 cm of the profile contained, on average, 73 percent of the 248 Mg C/ha in the 0-80-cm depth. Within the experimental site, relative differences of 21 percent in soil C for the 0-80-cm depth were

Table 21—Soil carbon to 80-cm depth in the preharvest forest stand at Fall River

Soil horizon	Depth	Block 1	Block 2	Block 3	Block 4	Mean ± SE (n =16 samples)
cm		*Mg/ha*				
A	0-12.3	76.1	71.6	50.6	71.8	67.5 ± 5.7
AB	>12.3-22.3	45.6	45.4	47.5	41.1	44.9 ± 1.3
AB	>22.3-42.3	82.7	65.7	64.7	64.2	69.4 ± 4.5
B	>42.3-62.3	37.3	44.4	44.3	42.9	42.2 ± 1.7
B	>62.3-80.0	31.8	27.7	17.9	20.7	24.5 ± 3.2
Total	0-80	273.5	254.8	225.0	240.7	248.5 ± 10.4

SE = standard error.

Table 22—Soil nitrogen to 80-cm depth in the preharvest forest stand at Fall River

Soil horizon	Depth	Block 1	Block 2	Block 3	Block 4	Mean ± SE (n =16 samples)
	cm	*kg/ha*				
A	0-12.3	2,668	3,112	2,185	3,288	2,813 ± 247
AB	>12.3-22.3	2,138	2,419	2,303	2,103	2,241 ± 73
AB	>22.3-42.3	3,887	3,860	3,480	3,545	3,693 ± 105
B	>42.3-62.3	2,060	3,138	2,758	2,714	2,668 ± 224
B	>62.3-80.0	1,585	2,186	1,578	1,564	1,728 ± 152
Total	0-80	12,338	14,715	12,304	13,214	13,143 ± 565

SE = standard error.

The mineral soil down to 80-cm depth was the largest store of C and N on the site.

observed between the soil pits with the most and the least C (soil pits near blocks 1 and 3, respectively).

The N store in the mineral soil down to 80-cm depth amounted to 13 143 kg/ha (table 22). Nitrogen distribution was similar to that for C with 66 percent of the N in the 0-42-cm depth. Differences in N stores were 20 percent between the blocks with the most and the least N (blocks 2 and 3, respectively). The C:N ratio varied from 24 in the A horizon to 14 in the lower B horizon, i.e., the 62.3- to 80.0-cm depth.

Total C and N Stores—

The mineral soil down to 80-cm depth was the largest store of C and N on the site accounting for 43 percent of the total C and 90 percent of the total N (table 23). The next largest store of C and N was the aboveground live-tree biomass, which composed 33 percent of the total C but only 4 percent of the total N. All biomass

Table 23—Summary of biomass and carbon and nitrogen stores in the preharvest forest stand at Fall River

	Biomass		Carbon		Nitrogen	
	Mg/ha	*%*	*Mg/ha*	*%*	*kg/ha*	*%*
Live trees	392.8	34.2	192.9	33.2	604.5	4.1
Dead trees	4.5	.4	2.1	.4	8.4	0
Snags	9.7	.8	4.8	.8	30.4	.2
Understory vegetation	.2	0	.1	0	4.9	0
Coarse woody debris[a]	22.3	2.0	11.4	1.9	74.3	.5
Old-growth stumps or snags	29.5	2.6	17.3	3.0	25.6	.2
Old-growth logs	73.2	6.4	36.9	6.3	122.3	.8
Forest floor	70.6	6.1	27.1	4.6	452.8	3.1
Coarse roots (> 5 mm)	82.2[b]	7.2	39.6[c]	6.8	180.8[d]	1.2
Small roots (2-5 mm) 0-45 cm	1.5	.1	.5[e]	.1	9.7[f]	.1
Fine roots (< 2mm) 0-45 cm	2.3[g]	.2	.8[e]	.1	14.9[f]	.1
Mineral soil 0-80 cm	458.7[h]	40.0	248.5	42.8	13 143.0	89.8
Total	1147.5		582		14 671.6	

[a] Excluding old-growth stumps, snags, and logs.
[b] Estimates of coarse root biomass (CRB) are the sum of the CRB values of individual trees; ln (CRB) (per tree in kg) = -3.55 + 2.33 ln (d.b.h.) ($n = 80$, $r^2 = 0.86$) (Thies and Cunningham 1996).
[c] A carbon (C) concentration of 48 percent (McDowell et al. 2001) was used to estimate the C store in coarse roots.
[d] A nitrogen (N) concentration of 0.22 percent (McDowell et al. 2001) was used to estimate the N store in coarse roots.
[e] A C concentration of 35 percent determined from root samplings at Fall River was used to estimate C stores in fine and small roots.
[f] A N concentration of 0.65 percent (McDowell et al. 2001) was used to estimate N stores in small and fine roots.
[g] Calculated from data in Keyes and Grier (1981).
[h] Organic matter.

stores above the mineral soil, including live and dead trees, understory vegetation, old-growth stumps and snags, CWD, old-growth logs, and forest floor, made up 50 percent of the C and 9 percent of the N. The old-growth logs, stumps, and snags that were remnants of the old-growth stand harvested five decades earlier contributed about 18 percent and 11 percent of the C and N stores above the mineral soil. We recognize we did not estimate insects, arthropods, birds, or other animals, but any of them would represent relatively small amounts of biomass, C, and N.

There were similar C stores above and within the mineral soil (0- to 80-cm depth) including roots (~ 290 Mg/ha).

Within the mineral soil, estimated fine, small, and coarse roots composed 14 percent of the C and 1.4 percent of the N to 80-cm depth. Carbon stores were about equally divided between those above the mineral soil and those within the mineral soil whereas the bulk of the N store was predominantly located in the mineral soil.

Discussion—

Allometric equations generated at Fall River for Douglas-fir and western hemlock[6] provided a reliable way to estimate biomass of aboveground tree components, a better alternative for our site than equations by Gholtz et al. (1979), which have been extensively used in the Pacific Northwest. Allometric equations for young Douglas-fir were available but they had been developed from low-site quality (site quality IV) stands (Redlin 1988). When used for the pretreatment stand at Fall River, the equations by Gholz et al. (1979) estimated 14 percent more biomass than did the allometric equations generated specifically for Fall River. Most of this difference occurred for Douglas-fir where biomass was overpredicted by 21 percent when using Gholz et al. (1979) equations. These differences were likely explained by the fact that Fall River equations were developed from an even-aged stand, but the equations by Gholz et al. (1979) used data from both even and uneven-aged stands, and from stands ranging in age from 22 to 110 years.

Aboveground biomass of the 47-year-old Douglas-fir/western hemlock stand at Fall River, i.e., 407 Mg/ha in live trees, dead trees, and snags, greatly exceeded the average biomass reported from other studies in the Pacific Northwest (Bancalari and Perry 1987, Barclay et al. 1986, Dice 1970, Heilman 1961, Swank 1960) for stands 22 to 52 years old. This result is consistent with the stand age, large stand basal area, and high site index at Fall River. Estimated total aboveground biomass of 90- to 110-year-old stands in the Northwestern United States (Fujimori et al. 1976) were, on average, 50 percent greater than that at Fall River, indicating that the stand at Fall River had not yet reached its maximum aboveground biomass accumulation potential. In this study, we neither measured nor estimated epiphyte biomass. This biomass store is usually very small, accounting for less than 0.1 percent of aboveground tree biomass (Smithwick et al. 2002).

Biomass of dead trees and snags from the 47-year-old stand at Fall River constituted small pools, i.e., 14 Mg/ha, composing 2.6 percent of the total aboveground biomass. Coarse woody debris, including old-growth logs, dead trees, and snags but excluding old-growth stumps, amounted to 110 Mg/ha. In a chronosequence study in the Washington Cascade Range, mass of CWD (logs > 10 cm in diameter) was estimated to be 92 Mg/ha in Douglas-fir stands less than 80 years old (Spies et al. 1988). Mature coastal Douglas-fir/western hemlock forests accumulated 42 to

[6] Harrison, R.B.; Terry, T.A.; Licata, C.W.; Flaming, B.L; Meade, R.; Guerrini, I.A.; Strahm, B.D.; Xue, D.; Adams, M.R.; Lolley, M.R.; Sidell, A.; Wagoner, G.L.; Briggs, D.; Turnblom, E.C.; Carpenter, P. Predicting biomass of Douglas-fir and western hemlock in the coastal hemlock zone of Washington: accounting for bias. Paper in preparation. University of Washington.

500 Mg/ha of log CWD and 25 to 105 Mg/ha of snags (Edmonds 1991). In old-growth stands, CWD mass can be quite high, i.e., 420 to 550 Mg/ha (Agee and Huff 1986, Keenan et al. 1993). The N store in CWD at Fall River, including standing dead trees, snags, CWD, old-growth logs, and old-growth stumps/snags, was 261 kg/ha, which was within the range found in northern coniferous forests up to 450 years old (Laiho and Prescott 2004), i.e., 20 to 450 kg N/ha with most stands having less than 170 kg N/ha in CWD. In a 450-year-old Douglas-fir stand in the H.J. Andrews Experimental Forest in Oregon, the N store in downed logs alone was 183 kg/ha (Means et al. 1992).

Given its slow decay rate, the role of CWD in nutrient cycling and supply may not be as critical as for other organic matter sources (Laiho and Prescott 2004). Coarse woody debris in natural stands adds fewer nutrients to the forest floor per kilogram of biomass than does fine litter because of the lower N concentration and higher C:N ratio of CWD. These nutrients in CWD are released slowly, and, therefore, CWD conserves nutrients during major disturbances (Harmon and Hua 1991). The inner bark (phloem) of recently downed wood may release nutrients at rates comparable to foliage litter, thus providing a relatively fast pulse of nutrients followed by a slow release from the inner parts of the wood, although more decay was found in the central portion of Douglas-fir logs with brown cubical rot than on the outside of the logs (Edmonds and Eglitis 1989). Significant nutrient export from CWD can take place through leaching, absorption by mycorrhizae and roots, fragmentation, insects, and fungal sporocarp production (Harmon et al. 1994).

Although N-fixation occurs in decaying logs and the forest floor in Douglas-fir forests of the Pacific Northwest (Jurgensen et al. 1992, Silvester et al. 1982, Sollins et al. 1987), rates of N-fixation are low, i.e., < 1 kg N/ha per year. These inputs are less than the N input from precipitation and dry deposition, estimated at 2 to 3 kg/ha per year at the H.J. Andrews Experimental Forest in Oregon (Sollins et al. 1987), and at 1.7 kg/ha per year in a 42-year-old Douglas-fir stand (Edmonds et al. 1989).

Dead wood provides critical habitat for birds, mammals, amphibians, invertebrates, and other organisms (Aubry and Hall 1991, Bull and Heater 2000, Bull et al. 1992, Carey and Johnson 1995). Dead wood can also reduce erosion, facilitate plant regeneration, and provide habitats for decomposer and heterotrophic organisms (Harmon et al. 1986). These aspects of CWD are important and need to be placed into context when broad-sense forest sustainability (Evans 1999) is considered.

At Fall River, coarse root biomass was not determined directly by excavation but estimated from an allometric equation relating Douglas-fir coarse root biomass and d.b.h. (Thies and Cunningham 1996). Using this function, we estimated 82 Mg/ha of coarse roots. This value is close to the upper limit reported for Douglas-fir by Santantonio et al. (1977) (range: 47 to 84 Mg/ha), although old-growth Douglas-fir forests in western Oregon were found to contain 97 to 193 Mg/ha of live coarse roots (Grier and Logan 1977).

Fine-root (< 2 mm in diameter) biomass in forests varies during the year but the degree of this variation seems site-specific. In western Washington, total fine root biomass (conifer plus angiosperm) ranged between 1.0 and 2.8 Mg/ha in high-productivity sites (Class II), and between 2.9 and 7.3 Mg/ha in low-productivity sites (Class IV) (Vogt et al. 1987). In a high-productivity site in Coastal Washington comparable to Fall River, biomass of live fine roots in a 40-year-old stand did not change appreciably among seasons, although fine root necromass increased significantly in the fall (Keyes and Grier 1981). In a low-productivity stand, both live and dead roots showed marked seasonal fluctuations, with live roots peaking in June at 8.3 Mg/ha. Estimates made by using minirhizotrons of standing fine-root biomass of mature (>100 years old) closed-canopy Douglas-fir stands in the Oregon Cascades varied significantly throughout the growing season and peaked in summer at about 20 Mg/ha in a low-resource site and at about 12 Mg/ha in a high-resource site (Tingey et al. 2005). Annual fine root production measured during two consecutive years averaged 23.1 Mg/ha in the low-resource site and 7.3 Mg/ha in the high-resource site. In that study, estimates of standing fine-root biomass made by using soil coring were 14.8 Mg/ha in the low-resource site and 5.3 Mg/ha in the high-resource site suggesting that core sampling during a few occasions per year led to underestimation of root biomass. For the summary of estimated biomass, C, and N stores before and after harvest at Fall River, we used fine-root data extrapolated from Keyes and Grier (1981).

Forest floor mass at Fall River (71 Mg/ha) was greater than the 27, 34, and 39 Mg/ha of forest floor (litter and humus) reported for 42-, 49- and 73-year-old Douglas-fir stands in the Cedar River watershed (Turner and Long 1975), and the 16 to 57 Mg/ha for mature coastal Douglas-fir/western hemlock stands (Edmonds 1991). An average of 45 Mg/ha was reported for 74 studies in cold temperate coniferous forests (Vogt et al. 1986). In addition to the fact that Fall River is a highly productive site and had received N-fertilization, the large values for forest floor mass at Fall River may be explained by the sampling method, which included any decomposed class 5 wood (red rot) within and under the litter layer down to the mineral soil. It was important to include this material as part of the forest floor sample, as there was considerable red-rot material incorporated into the forest floor at the site and it would not have been accounted for in any of the other biomass pool sampled. Unfortunately, the mass of red rot in the preharvest sampling was not estimated.

The upper 80 cm of the soil profile at Fall River contained 42 percent of the site C and 89 percent of the site N.

The intact forest floor had a C concentration of 38.5 percent, within the range of 35.8 percent (for the O_i layer) and 47.7 percent (for the O_a and O_e layers) found in a 40-year-old Douglas-fir in south-central Washington (Klopatek 2002). The forest floor N concentration at Fall River was 0.66 percent versus 1.20 percent in the previous study, but the stand in south-central Washington was composed of 33 percent N-fixing red alder (*Alnus rubra* Bong.). Forest floor C and N stores at Fall River, i.e., 27 Mg N/ha and 453 kg C/ha, surpassed the upper limits found in 13 second-growth (45- to 72-year-old) Douglas-fir stands (Homann et al. 2001), and in 154 Douglas-fir and western hemlock stands (Edmonds and Chappell 1993) in western Washington and Oregon, although a survey of 65 cold temperate coniferous stands found an average of 504 kg N/ha in the forest floor (Vogt et al. 1986). In the 13 second-growth stands, C stores ranged between 5 and 18 Mg/ha, and N stores ranged between 130 and 360 kg/ha. Most of these stands, however, were not on Andisols, and all of the sites but one had site indices lower than that at Fall River. In addition, red rot may not have been fully sampled in these other studies. Forest floor C at Fall River was also markedly higher than C stores in two 20- and 40-year-old Douglas-fir stands growing on Entic Vitrands in south-central Washington (Klopatek 2002), but the N store at Fall River was similar to that in the 40-year-old stand (approximately 450 kg/ha). Forest floor C and N stores averaged 9.7 Mg/ha and 244 kg/ha, respectively, in 19 Douglas-fir stands in coastal Washington (Edmonds and Chappell 1993).

The upper 80 cm of the soil profile at Fall River contained 248 Mg C/ha, i.e., 42 percent of the site total, and 13 Mg N/ha, i.e., 89 percent of the site total. The N store in the upper 80 cm of the soil profile is particularly noteworthy and relates to the Boistfort soil's capacity to retain organic matter. At Fall River, C in live biomass and mineral soil to 80-cm depth were similar fractions of total stand C, i.e., 34 and 40 percent, respectively. Carbon stores in other Douglas-fir/western hemlock forests averaged approximately 60 percent for live biomass, 20 percent for woody detritus, 5 percent for forest floor, and 15 percent for mineral soil to 1-m depth, according to field estimates (Grier and Logan 1977, Harmon et al. 1998, Smithwick et al. 2002) or modeling (Harmon and Marks 2002). The total site C store at Fall River was 582 Mg C/ha, lower than the average of 820 Mg C/ha

Figure 10—View of biomass-removal treatments at the Fall River research area: commercial bole-only removal (top left), commercial bole up to 5-cm top removal (top right), total-tree removal (bottom left), and total-tree-plus removal (bottom right).

estimated for seven 230- to 280-year-old coniferous forests in the Olympic Peninsula (Smithwick et al. 2002), although soil C was measured to 1 m-depth in these studies.

Biomass-Removal Treatments

Treatment Description and Installation

Biomass-removal treatments were implemented from May to July of 1999. Trees were directionally hand-felled so that all treetops remained within the plot. The four biomass-removal treatments (fig. 10) were as follows:

(1) Bole-only harvesting (BO): Tree boles down to a merchantable limit of 8 to 13 cm in top diameter and 3 m in length were removed. Remaining tops, broken logs < 3 m in length, butt cuts, and all remnant CWD were left in place.
(2) Bole-only to 5-cm top (BO5): Tree boles up to a 5-cm top diameter were removed as well as all broken boles and butt cuts to a 5-cm top.
(3) Total-tree (TT): Complete tree boles, all live limbs and foliage, and most large dead limbs greater than 2.5 cm in diameter were removed. Small green limbs and fresh foliage were removed by hand. Most remnant CWD was left in place. The shovel excavator inadvertently removed some forest floor and remnant CWD when removing limbs and tops.
(4) Total-tree plus (TT+): Harvesting removed the entire aboveground portion of the tree including all live limbs and foliage, and most dead limbs. In addition, most live or dead limbs greater than 0.6 cm remaining on the plot were manually removed. All remaining CWD, including remnant old-growth logs and surface red rot were also removed with the exception of new stumps, old-growth stumps and snags, and rotted material that could not be taken intact. The larger CWD was removed mechanically by using a shovel excavator positioned outside the internal measurement plot. Red rot below the ground surface was left in place. In addition to the logging slash and CWD removed by the shovel excavator, a considerable amount of the fine slash and CWD was removed by hand. Some forest floor was inadvertently removed by the shovel excavator as in the previous treatment.

Trees and CWD were removed by cable or shovel yarder depending on treatment. Shovel yarders were only used within internal measurement plots for ground-based harvesting where the soil compaction and soil compaction-plus-tillage treatments were implemented (Terry et al. 2001). All biomass-removal treatments not receiving compaction were cable-yarded by using a CAT 330L (Caterpillar) two-drum shovel yarder, and a tail-hold tractor to minimize site disturbance. Moreover, a shovel excavator with a piling-rake head traversed all treatment plots outside the internal measurement plot to scatter slash uniformly within the plot after harvesting, and to further remove woody materials. No ground-equipment traffic occurred in any of the internal 0.10-ha measurement plots except as required to implement the soil compaction, and soil compaction-plus-tillage treatments.

The TT and TT+ treatments were included in the study to extend the range of biomass-removal regimes rather than simulate operational treatments. The TT treatment was not equivalent to an operational whole-tree harvest because more material was removed in TT than the material that would have been removed in an actual operation. The TT+ treatment in this study did create conditions that are similar to what would be achieved in areas between piles in some slash-piling operations. In this study, all biomass material removed from treatment plots was piled in buffer areas outside the study area and burned. None of the biomass-removal treatments removed old-growth stumps/snags.

All the biomass-removal treatments received intensive vegetation control for the first 5 years after harvest (2000-2004) except for the one set of the BO treatment that was specified not to receive vegetation control. The purpose was to control all competing vegetation, and not to simulate typical operational vegetation control. Two weeks before planting the Douglas-fir seedlings, Oust® (0.21 kg/ha [DuPont Crop Protection]) and Accord Concentrate® (4.67 L/ha [Dow AgroSciences LLC]) were broadcast by using backpack sprayers. In 2001, Atrazine® (9.3 L/ha [Syngenta Crop Protection]) was uniformly sprayed in March and followed in April and May by spot application of Accord Concentrate® (0.75 percent by volume in water). In March 2002, Atrazine® (9.3 L/ha) and Oust® (0.17 kg/ha) were broadcast and followed with spot applications of Transline® (1 percent by volume in water [Dow AgroSciences LLC]) in April-May and Accord Concentrate® (0.75 percent in water) in June-July. In March 2003, a directed band of Velpar® (7.0 L/ha [DuPont Crop Protection]) was applied between rows and followed with spot applications to shrubs of Transline® (1 percent by volume in water) in April-May and Accord Concentrate® (0.75 percent by volume in water) in June. In April 2004, Velpar® (5.85 L/ha) was applied in a directed band between rows. Herbicide applications differed by year to avoid development of species resistance to an individual herbicide.

In the BO treatment with vegetation control and no soil compaction, logs were cable-removed with a CAT 330L two-drum shovel yarder, and a tail-hold tractor to minimize site disturbance (fig. 11).

Two additional treatments were imposed on BO plots with vegetation control:

- Soil compaction: Trees were yarded in May 1999 with a 44-ton CAT 330L shovel with 70-cm-wide pads (fig. 12). The soil water content at time of yarding was at or near field capacity. Eight equally spaced traffic lanes were flagged in each trafficked plot to make soil disturbance comparable across blocks. Every other lane was trafficked twice to more closely simulate traffic patterns that operationally occur when both a feller-buncher and a shovel yarder are used during harvesting (fig. 13).
- Soil compaction plus tillage: In this treatment, the compaction treatment described above was followed by thorough soil tillage to 60-cm depth on

Figure 11—Cable harvesting at the Fall River research area.

Figure 12—Ground-based forest harvesting (left) and traffic lane (right) at the Fall River research area.

the areas trafficked by the shovel with a small CAT 322BL excavator shovel fitted with a bucket (Pacific Services and Manufacturing, Inc.) with two 60-cm-long tillage tines (fig. 14).

To evaluate the effects of biomass removal, soil compaction and tillage, and vegetation control on Douglas-fir growth, the site occupied by the stand harvested in 1999 was planted in March 2000 with 1+1 seedlings (grown in the nursery for 1 year, then lifted and transplanted at lower density in the nursery and grown another year). Seedlings were selected to ensure they fell within designated height and basal diameter ranges, planted at 2.5 by 2.5 m (1,600 trees/ha) and individually numbered and tagged to allow accurate plot maps and tree-specific data to be obtained.

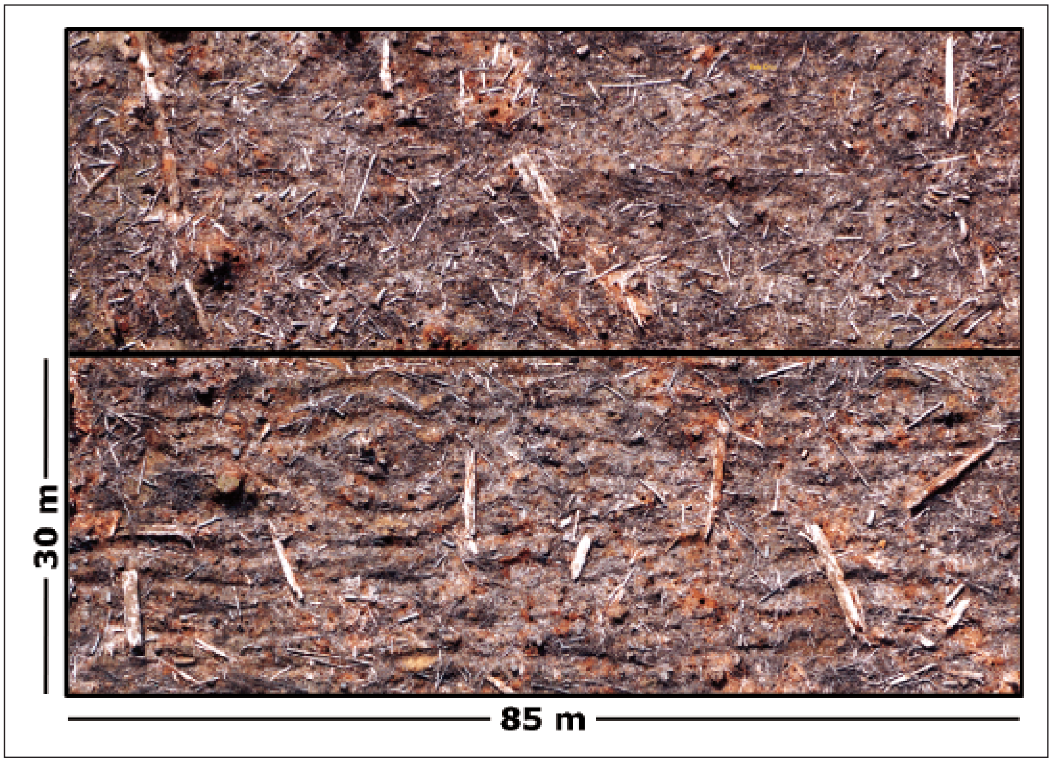

Figure 13—Aerial views of plots after cable (top, no traffic lanes visible) and ground-based harvesting (bottom, traffic lanes visible along the main plot axis) at the Fall River research area.

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 $VWD = 9.869 \times N_o \times a \times (d^2/8L)$ [4]

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

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

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 5^{th}, then every 6^{th} 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/m³			
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					Total biomass
	1+2	3	4	Old-growth logs	Recent stumps	
	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).

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

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.

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

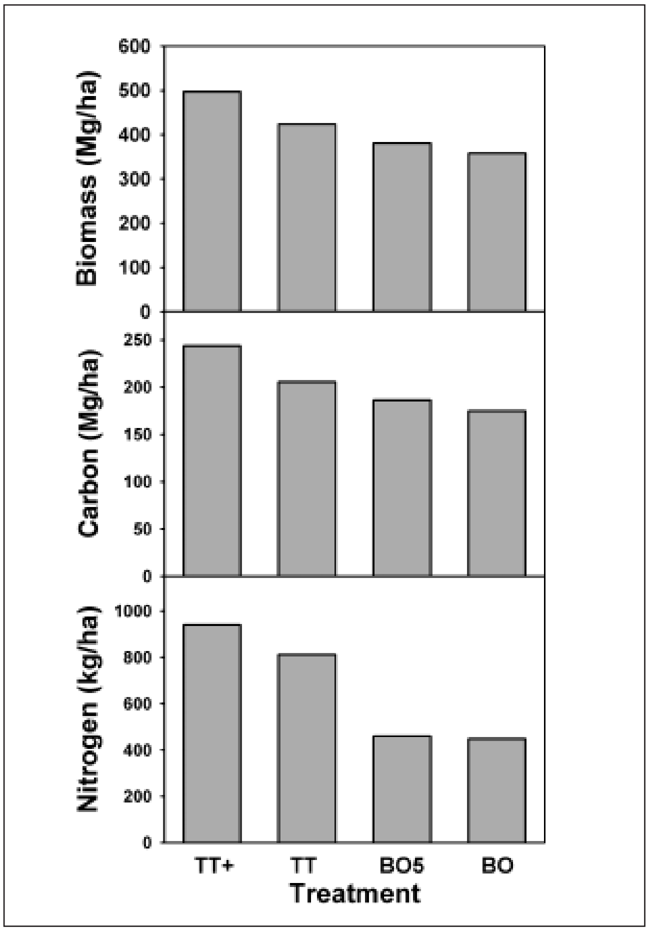

Figure 15—Biomass, carbon, and nitrogen removals at harvest at the Fall River research area. Treatments are bole-only removal (BO), bole to 5-cm top removal (BO5), total-tree removal (TT), and total-tree plus all-legacy-wood removal (TT+).

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.

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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

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