Biomass Removal, Soil Compaction, and Vegetation Control Effects on Five-Year Growth of Douglas-fir in Coastal Washington

Adrian Ares, Thomas Terry, Constance Harrington, Warren Devine, David Peter, and John Bailey

Abstract. Sustainable forest production requires an understanding of the effects of site disturbance on tree growth and the consequences of soil amelioration and vegetation control practices. We assessed the impacts of biomass removals at harvest, soil compaction and tillage, and vegetation control on early growth of Douglas-fir in coastal Washington. Harvest treatments included removal of commercial bole only (BO), bole only up to 5-cm top diameter (BO5), total tree (TT), and total tree plus all legacy coarse woody debris (TTP). Vegetation control (VC) effects were tested in BO, while soil compaction (BO/SC) and compaction plus tillage (BO/SCT) were imposed in BO/VC. Five years after planting, biomass removal and soil compaction/tillage effects on tree growth were relatively small. At year 5, mean stem basal diameter in BO was greater than in TT, whereas mean height was similar in BO and BO/SC, but increased in BO/SCT. Control of competing vegetation markedly increased tree growth. At year 5, mean tree stem diameter at 1.3-m height (dbh) and height in BO/no vegetation control (NVC) were 34 mm and 308 cm, respectively, compared to 45 mm and 357 cm in BO/VC (P <0.01). Mean relative growth rate in stem diameter for trees in BO/VC was greater than in BO/NVC in years 2–4, but this trend reversed in year 5, suggesting that tree intraspecific competition may be greater in BO/VC than in BO/NVC. Vegetation control also increased second-flushing (i.e., the flushing of set buds in late summer) in years 4 and 5. Vegetation competition effects on tree growth appeared to be related to changes in available soil water rather than to competition for nutrients. FOR. SCI. 53(5):600–610.

Key words: long-term forest productivity, forest soils, vegetation, *Pseudotsuga menziesii*, soil water

INTENSIVE FOREST MANAGEMENT aimed to increase wood production and improve operational efficiency may affect forest sustainability depending, among other factors, on initial site conditions and treatment regimes. Excessive removal of C and nutrients in slash, tree foliage, wood, forest floor, and topsoil, and soil disturbance/compaction caused by equipment traffic are two of the major factors that may cause site degradation and reduction in forest productivity (Vance 2000, Miller et al. 2004). Mechanical or chemical vegetation control, fertilization, and soil amelioration (e.g., bedding, ripping) can increase productivity above base levels and reduce or eliminate negative impacts caused by biomass removal or soil compaction (DeWit and Terry 1983, Rose and Rosner 2005). These practices, however, need to be assessed throughout the rotation to determine their long-term consequences on site quality and tree growth.

On some sites in the Pacific Northwest region of the United States, more harvest residues are currently maintained after logging than in the past because of air quality concerns about slash burning and efforts to reduce site preparation costs (Talbert and Marshall 2005). Concurrently, rotation ages have declined while utilization of merchantable material has increased. Also, heavy equipment is customarily used for site preparation and timber harvest, whereas vegetation control is practiced in many new tree plantations. Additional knowledge is required on the effects of residue conservation, biomass removal, soil disturbance/compaction, and vegetation control on the sustainability of forest production.

Harvest intensity and residue management can affect site nutrient stores and dynamics, microsite climate, and tree growth. Whole-tree harvesting removes more biomass and nutrients from the site than bole-only removal (Freedman et al. 1981, Egnell and Valinger 2003). Residue retention can conserve nutrients by reducing losses in leaching (Carlyle et al. 1998, Blumfield and Xu 2003), although the opposite effect has also been observed (Rosén and Lundmark-Thelin 1987, Strahm et al. 2005). Differences in N leaching after whole-tree and conventional harvesting were generally small in 11 hardwood and conifer stands across the United States (Mann et al. 1988). Nitrogen mineralization rates usually increase after forest harvest (Parsons et al. 1994, Prescott 1997), but drop in subsequent years (Smethurst and

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Nambiar 1990). In contrast, microbial decomposition of woody debris with high C:N ratios can temporarily immobilize nutrients (O'Connell 1997). Residue retention usually moderates surface soil temperatures (Pérez-Batallón et al. 2001, Powers 2002) and conserves soil water, although effects can be transitory and restricted to the upper soil (Blumfield and Xu 2003). When harvest residues are retained, early tree growth can increase (Proe and Dutch 1994, Mendham et al. 2003), or remain unchanged (Smith et al. 1994, Zabowski et al. 2000) depending on the site conditions.

Ground-based forest harvesting affects soil physical, chemical, and biological characteristics (Greacen and Sands 1980, Lenhard 1986, Torbet and Wood 1992). Effects of soil compaction/disturbance on soil properties and tree growth can be positive, detrimental, or inconsequential (Miller et al. 2004). Negative impacts can be a consequence of reduced infiltration (Startsev and McNabb 2000), oxygen availability (Herbauts et al. 1996), and N mineralization (Tan et al. 2005), or increased impedance for root growth (Heilman 1981). Positive effects of soil compaction may result from increased water-holding capacity (Gomez et al. 2002b), unsaturated water flow (Sands et al. 1979), root contact with soil (Bhadoria 1986), and N uptake (Gomez et al. 2002a).

Control of competing vegetation has been found to greatly increase tree growth (Wagner et al. 2006). In loblolly pine (*Pinus taeda* L.), complete vegetation control during the first three growing seasons increased stand wood volume at age 12 by 39–45% (Martin and Shiver 2002). Stand volume of Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) 6 years after receiving manual vegetation control at ages 3 to 5 was 4.1-fold greater than that of the control (Stein 1999). Tree growth gains after reductions in cover or biomass of competing vegetation have been attributed to increased soil nutrients (Smethurst and Nambiar 1995, Zutter et al. 1999, Gurlevik et al. 2004) or water supply (Newton and Preest 1988, Watt et al. 2003, Roberts et al. 2005). Increases in soil nutrient and water availability may occur together (Morris et al. 1993, Ares and Fownes 2001), and, therefore, it is difficult to determine which of the two limitations affect tree growth the most.

In addition to effects on tree growth, changes in soil water or nutrient supply can affect tree phenology. Second flushing is the opening during late summer of newly formed buds that otherwise would not have opened until the next spring (Adams and Bastien 1994). Second flushing can result in greater height growth for Douglas-fir, but it can negatively affect stem form and increase the susceptibility of stems to late-season drought and early-fall frost (Kaya et al. 1989, Anekonda et al. 1998). Second flushing depends on tree genotype (Li and Adams 1993) and environmental conditions (Roth and Newton 1996).

The study at the Fall River research site (Ares et al. 2007) in the coast range of Washington is one of the more than 40 affiliate installations that are part of the Long-Term Soil Productivity (LSTP) program carried out on major soil and vegetation types of the United States and Canada since 1989 (Powers et al. 2005). The Fall River study is a long-term, replicated experiment where treatments have been imposed on a site with low-spatial variability and known history, while potential confounding effects of big-game browse have been eliminated. This research strategy renders more consistent results than the retrospective approach (Powers 1989) that may not determine the original type, degree, and extent of disturbance, and overlook possible differential effects on tree growth from plant competition, disease, herbivory, and other factors (Heninger et al. 1997).

The specific objectives of this study are to:

(1) examine to what extent biomass removals at harvest, soil compaction, and vegetation competition affect survival, growth, foliar nutrients, and second-flushing in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and understand the mechanisms of response,

(2) determine whether remediation practices such as tillage (and possibly fertilization) are needed to sustain tree growth.

We hypothesized that tree survival and growth, and foliar nutrient concentration will decrease with increasing biomass removals at harvest, in disturbed/compacted soil compared to undisturbed/noncompacted soil, and when competing vegetation is not controlled. Also, second-flushing frequency would increase with vegetation control. Information generated in this study adds to regional strategic databases in the Pacific Northwest that are used to refine forest management (i.e., harvesting, site preparation, vegetation control, thinning) prescriptions across sites to meet production objectives.

Materials and Methods

Site Description

The Fall River research site is in the Coast Range of Washington State at 46°43′N lat. and 123°25′W long. The climate is maritime with wet, mild winters and warm, relatively dry summers. Mean annual temperature is 9.2°C with monthly means of 2.6°C in the coldest month (January) and 16°C in the warmest month (August). Estimated mean annual precipitation is 2,260 mm mostly as rain (USDA Natural Resources Conservation Service (NRCS)/OSU SCAS 1999). Weather data at Fall River have been recorded in this study since 2001. For the 2001–2004 period (i.e., plantation age 2 to 5), the highest and lowest annual precipitation were in 2003 (1,973 mm) and 2002 (1,388 mm), respectively. Total precipitation from May 1 to September 30 (i.e., the approximate growing season) was 314 mm in 2000, 312 mm in 2001, 177 mm in 2002, 183 mm in 2003, and 430 mm in 2004. In 2002 (i.e., age 3), July and August were particularly dry with only 14 mm of precipitation recorded in these two months.

The experimental site is between 305 and 362 m elevation on gentle slopes (<10%) facing west. The soil is a medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand (Soil Survey Staff 2003) of the Boistfort series developed from weathered Miocene basalt and with some volcanic ash in the upper horizons (Steinbrenner and Gehrke 1973, Logan 1987). The soil is deep, well-drained, mostly stone-free, and has low bulk density, high organic C content and high water-holding capacity. The A horizon (0–16 cm) has 13% sand, 52% silt, 35% clay, and 9.6%

organic C. On average, available water capacity at -10 to $-1{,}500$ kPa in the A and AB ($>16-44$ cm) horizons is 0.33 $m^3\ m^{-3}$ and pH is 5. Total soil N to 80-cm depth is 13,140 kg ha^{-1}. The site quality class for Douglas-fir is I to II+ with an average site index of 42 m at breast-height age 50 years (King 1966).

The Fall River site is within the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) vegetation zone (Franklin and Dyrness 1973). The plant association is western hemlock/western sword fern (*Polystichum munitum*) (Kaulf.) (Presl.)/oxalis (*Oxalis oregana* Nutt.) (Henderson et al. 1989). The old-growth stand previously occupying the site was cable yarded in 1952–53 followed by broadcast burning and planting of Douglas-fir. The Douglas-fir stand was precommercially thinned in 1971, and fertilized four times between 1970 and 1995 with a total of 820 kg N ha^{-1} as urea (Ares et al. 2007).

Study Design and Treatments

The study was installed from April to July of 1999. The study was designed to contain 12 treatments with seven treatments imposed as of 2005. Five fertilization treatments will be applied if nutrient deficiencies become evident, or significant differences in tree growth exist among biomass-removal treatments after crown closure. The study follows a randomized complete block design with four blocks (Fig. 1). Blocking was based on the proportion of Douglas-fir and western hemlock in the preharvest stand and slope position. Treatment plots are 30 m by 85 m (0.25 ha) with an internal 15 m $\times$ 70 m (0.10 ha) measurement area.

All harvested trees were directionally hand-felled between May and July of 1999 to keep all plot biomass within the plot boundaries. Biomass removal treatments were: (i) commercial bole-only up to 8- to 13-cm small-end diameter removal (BO), (ii) bole-only to 5-cm small-end diameter removal (BO5), (iii) total tree (aboveground portion) removal (TT), and (iv) total tree plus all legacy wood removal (TTP). For these treatments, logs were cable-removed with a CAT 330L (Caterpillar, Peoria, IL) two-drum shovel yarder, and a CAT tail-hold tractor to minimize site disturbance. Two additional treatments were (v) soil compaction (BO/SC), and (vi) soil compaction plus tillage (BO/SCT) both on commercial bole-only plots with vegetation control. In plots with soil compaction, trees were yarded in May 1999 with a CAT 330L shovel with 70-cm-wide pads when the soil was near field water capacity. Soil tillage to 60-cm depth was applied on traffic lanes with a small CAT 322BL excavator shovel fitted with a PSM bucket with two 70-cm-long tillage tines.

All the biomass-removal treatment plots received intensive vegetation control for the first 5 years after harvest (2000–2004) except for the plots in the BO treatment that were specified not to receive vegetation control (BO/NVC); i.e., treatment vii. Vegetation control was applied for a longer period and was more intensive than in typical operational vegetation control, which normally is applied the first two years after planting. Herbicide treatments differed by year to avoid proliferation of species tolerant to a specific herbicide. Two weeks before planting, Oust (0.21 kg ha^{-1}; DuPont Crop Protection, Wilmington, DE) and Accord Concentrate (4.67 L ha^{-1}; Dow AgroSciences LLC, Indianapolis, IN) were broadcast using backpack sprayers. In 2001, Atrazine (9.3 L ha^{-1}; Syngenta Crop Protection, Greensboro, NC) was uniformly sprayed in March and followed in April and May by spot applications of Accord Concentrate (0.75% by volume; in water). In 2002, Atrazine (9.3 L ha^{-1}) and Oust (0.17 kg ha^{-1}) were broadcast in March and followed with spot applications of Transline (1% in water; Dow AgroSciences LLC, Indianapolis, IN) in April–May and Accord Concentrate (0.75% in water) in June–July. In March 2003, a directed-band of Velpar (7.0 L ha^{-1}; DuPont Crop Protection, Wilmington, DE) was applied between rows and followed with spot applications of Transline (1% in water; applied to shrubs) in April–May and Accord Concentrate (0.75% in water) in June. In April 2004, Velpar (5.85 L ha^{-1}) was applied in a directed-band between rows. All herbicides were applied following procedures aimed to minimize negative effects on Douglas-fir seedlings.

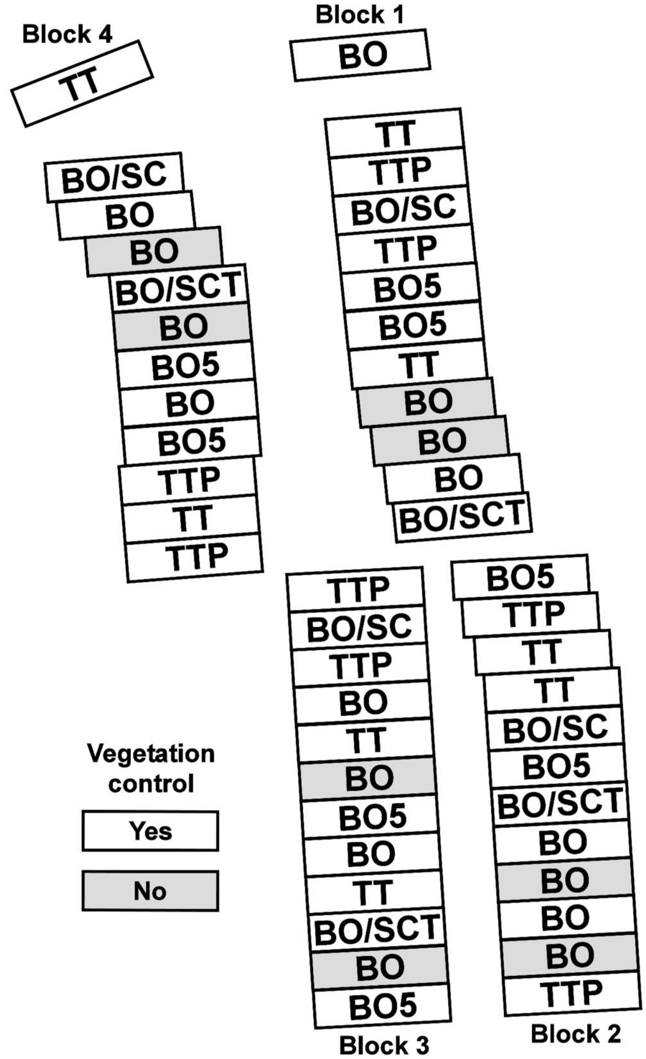

Figure 1. Layout of the Fall River study including biomass removal (BO, bole-only removal; BO5, bole-only removal to 5-cm top; TT, total tree removal; and TTP, total tree plus removal), SC, soil compaction; SCT, soil compaction and tillage, and vegetation control treatments.

Douglas-fir seedlings (1 + 1 stock type) were planted at

2.5 m × 2.5 m spacing (1,600 trees ha^{-1}) in March 2000. All seedlings were hand planted using a shovel. Seedlings were produced from a mixed seed lot of 23 first-generation half-sib families. Seedlings were graded for uniformity and only those between 5 and 10 mm in groundline diameter, and 35 and 51 cm in height were planted. The study area remained fenced until year 5 to eliminate deer and elk browsing and reduce rabbit clipping.

Measurements and Data Analyses

Height of Douglas-fir trees was measured with a telescopic measuring pole in all treatments in years 1 to 5. Stem diameter was measured at marked locations with a diameter tape in BO/VC, BO/NVC, TTP, and BO/SC in years 1 to 5, and in BO/SCT, BO5, and TT in years 3 and 5. Stem measurements included stem basal diameter at 15 cm aboveground level (BD) in years 1 to 3, and stem diameter at 1.3 m aboveground (dbh) in years 2 to 5. Both BD and dbh were measured in BO/VC, BO/NVC, and TTP in years 2 through 5 on a specified subset of trees within circular 15-m diameter subplots located 27.5 m from the center of the plot west boundary. To be able to represent the stem diameter growth from years 1 to 5, basal diameter at age 4 and 5 was estimated from dbh using the following equations, which were obtained by regressing BD against dbh measured on the tree subsets for years 4 and 5:

For year 4,

$$\text{BD (mm)} = 32.139 + 1.0577 \text{ DBH (mm)} \quad \text{for trees in BO/VC, BO5, TT and TTP} \quad (r^2 = 0.61, N = 157) \tag{1}$$

$$\text{BD (mm)} = 22.477 + 1.0102 \text{ DBH (mm)} \quad \text{for trees in BO/NVC} \quad (r^2 = 0.62, N = 78) \tag{2}$$

For year 5,

$$\text{BD (mm)} = 29.932 + 1.1527 \text{ DBH} \quad \text{for trees in BO/VC, BO5, TT and TTP} \quad (r^2 = 0.82, N = 80) \tag{3}$$

$$\text{BD (mm)} = 21.815 + 1.1928 \text{ DBH (mm)} \quad \text{for trees in BO/NVC} \quad (r^2 = 0.72, N = 80) \tag{4}$$

Equation coefficients for BO/VC and BO/NVC were significantly different; therefore, separate equations were used for these treatments. For BO/VC and TTP, equation coefficients did not differ, and equations for BO/VC were also used for BO5, TT, and TTP. Mean relative growth rate (MRGR) (Couston 1981) either in height or stem diameter (BD or dbh) was calculated as:

$$\text{MRGR} = \frac{\ln(\text{height in cm, or diameter in mm at time 2}) - \ln(\text{height in cm, or diameter in mm at time 1})}{\text{weeks between measurements}} \tag{5}$$

Stem volume at year 5 was calculated from dbh and height data using the equations for Douglas-fir trees less than 5.5 m in height (Bruce and DeMars 1974). Douglas-fir foliage (needles plus twigs) was collected from the upper third of the crown of 15–20 representative trees randomly chosen per plot in February 2003 (i.e., age 3), March 2004 (i.e., age 4) and January 2005 (i.e., age 5) from all plots in three treatments: BO/VC, BO/NVC, and TTP. Foliage samples were dried at 65°C, and needles were then separated from the twigs. Samples composited per plot were analyzed for N and S concentration with a LECO CNS-2000 Macro Analyzer (LECO Corporation, St. Joseph, MI), and for P, K, Ca, Mg, Bo, Cu, and Mn by inductively coupled plasma with an Optima 3,000-DV (Perkin Elmer, Inc., Shelton, CT).

Biomass removals were not measured directly during the harvest operation. Therefore, we calculated N removal in each biomass-removal treatment by subtracting the N stored in coarse woody debris and forest floor left after harvest in the treatment from the sum of the standing crop N stored in bole wood, bark, live and dead branches, foliage, dead trees and snags, coarse woody debris, and forest floor prior to harvest (Ares et al. 2007). Preharvest estimates of these stores were based on the plot average for all 48 study plots.

Volumetric soil water content was measured during the growing season (May to October) in years 2 (2001) and 3 (2002) with a Hydrosense CS620 instrument (Campbell Scientific, Logan, UT) with 20-cm tines as described in Roberts et al. (2005). In years 3, 4, and 5 (2002–2004), VSW was measured at three- to four-week intervals during the growing season using a 100-cm PR1 Profile Probe with a HH2 meter (Delta-T Devices, Ltd., Cambridge, UK) as described in Devine and Harrington (2006). The probe has capacitance sensors at 10-, 20-, 30-, 40-, 60-, and 100-cm positions that take readings simultaneously at these soil depths. The probes were inserted into 100-cm fiberglass access tubes installed vertically in the soil and equidistant from the four nearest trees. Three readings were made in every measurement, rotating the probe 120° between readings. In year 3, there was one access tube per plot, but a second tube was installed in each plot in December 2003 approximately 5–6 meters from the initial tube but also equidistant from the four nearest trees. Readings were not taken less than 48 hr after rain events greater than 10 mm. Volumetric water data for 20-, 40-, and 60-cm are reported.

Soil bulk density samples were taken with a 31.2-mm diameter punch-tube volumetric sampler in 13 sampling spots randomly located in all plots. Samples were then oven-dried at 105°C for determinations of bulk density and soil gravimetric and volumetric water content. More details on bulk density measurements are provided in Ares et al. (2005).

Understory vegetation was surveyed in circular 177-m^2 subplots located inside the 24 sampled treatment plots in

July of 2000–2005 following USFS protocols (Henderson et al. 1989). Canopy cover was assessed on all subplots each year except in 2003. Species present in year 3 and 5 were assumed present in year 4. Species present in year 3, but not in year 5 or vice versa were considered absent in year 4. Cover was defined as the vertically projected polygon around the outer tips of all aboveground parts of vascular plants. The term "canopy cover" is used here to refer to the collective cover of all vascular plants by tree, shrub, and herb categories (never to exceed 100% per category). Biomass of understory vegetation was sampled within 0.2 m × 0.5 m PVC frames in 20 locations randomly selected in each plot in 2002. In 2004, the sampling area was increased to 1.0 m × 1.0 m for shrubs in BO/VC and BO/NVC, and for herbaceous vegetation in BO/VC. Biomass samples were dried at 65°C until constant weight.

Treatment effects on tree size and growth, foliar N, competing vegetation canopy cover and biomass, soil water content and temperature, and frequency of second-shoot flushing were analyzed as a mixed model with treatments as fixed effects and block as a random effect. Because fertilization treatments have not been yet applied, five treatments (BO, BO5, TT, TTP and BO without vegetation control) were represented by two plots in each block. Comparison of treatment means for each year of the study was made using one degree of freedom orthogonal contrasts. The arc-sine square-root transformation was used for frequency data. Procedure MIXED in SAS 8.2 (SAS Institute 1999) that estimates variance components using restricted maximum likelihood methods was used for the analyses of variance. An $\alpha = 0.05$ was used in all statistical analyses for determining significance.

Results

Tree Survival

Tree survival up to year 5 did not differ among treatments. In biomass-removal treatments, survival ranged from 94.0% in BO to 94.9% in TTP. Survival was 94.9% in BO/SC, 93.4% in BO/SCT, and 94.4% in BO/NVC.

Biomass-Removal Effects on Tree Growth, Foliar N, and Soil Microclimate

Biomass removals at harvest had relatively small effects on early growth of Douglas-fir (Fig. 2). Results for BO5 were similar to those for BO and are not presented. At year 5, mean dbh and height were 44.8 mm and 357 cm in BO, 42.6 mm and 347 cm in TT, and 42.9 mm and 350 in TTP. At year 5, mean BD (calculated from the relationships between BD and dbh) was greater in BO than in TT, but there were no differences in BD between TTP and the other two biomass-removal treatments (Fig. 2). Stand stem volume at year 5 was 5.6 m^3 ha^{-1} in BO, and 5.3 m^3 ha^{-1} in both TT and TTP.

Mean foliar N concentration of trees in BO and TTP did not differ in any of the sampling dates in years 3, 4, and 5. Foliar N concentration tended to decrease with age for these biomass-removal treatments. Percent foliar N concentration in BO was 2.30 ± 0.11, 1.99 ± 0.10, and 1.58 ± 0.11 in

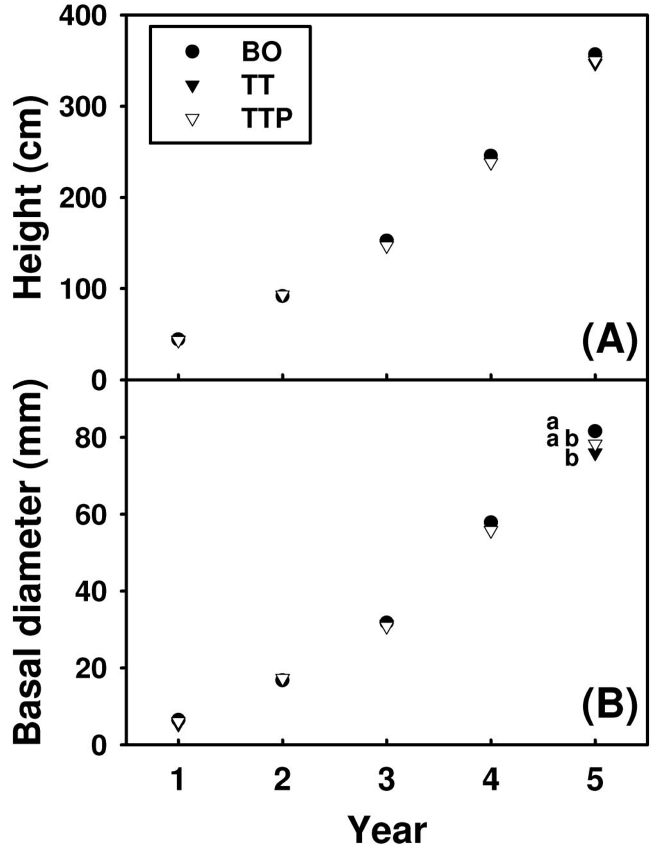

Figure 2. Mean height and stem basal diameter of Douglas-fir trees in biomass-removal treatments during the first five growing seasons (years 2000 to 2004) at Fall River. Means with the same letter are not significantly different at $P \leq 0.05$.

January 2003 (age 3), March 2004 (age 4), and January 2005 (age 5), respectively, whereas it was 2.28 ± 0.10, 1.97 ± 0.09, and 1.60 ± 0.10 in TTP for the same sampling dates. There were no relevant differences in concentrations of other foliar macro and micronutrients observed among biomass-removal treatments (Data not shown).

Nitrogen removals at harvest were 432 kg ha^{-1} in BO, 445 kg ha^{-1} in BO5, 796 kg ha^{-1} in TT, and 925 kg ha^{-1} in TTP. These N amounts represented only 3–6% of the total N store of the site (i.e., in aboveground live and dead vegetation, coarse woody debris, forest floor, roots, and soil to the 80-cm depth). If the forest floor had been removed, N removal as a percent of the total site N would have increased to 8%.

Volumetric soil water content measured at the 0–20-cm depth with a Hydrosense was greater in BO than in TTP during the growing season of years 2 (averaging 0.39 and 0.38 m^3 m^{-3}, respectively) and 3 (averaging 0.38 and 0.36 m^3 m^{-3}, respectively). Differences were not significant in years 4 and 5 when a profile probe was used in the measurements.

Soil Compaction Effects on Tree Growth

Soil bulk density increased significantly with compaction caused by ground-based harvesting from 0.56 ± 0.01, 0.65 ± 0.01, and 0.68 ± 0.01 Mg m^{-3} at 0–10-, 10–20-, and 20–30-cm depth, respectively, in the noncompacted soil to maximum values of 0.77 ± 0.02, 0.83 ± 0.01, and 0.86 ± 0.02 Mg m^{-3} at the same depths in the most compacted microsites ($P \leq 0.05$). Soil compaction or tillage following compaction did not affect mean BD of Douglas-fir at the plot level in any year (Table 1). Mean height was similar for all treatments in all years but year 5, when mean height in BO/SCT was greater than in the treatment without soil compaction. Stand stem volume at year 5 was 5.5 m^3 ha^{-1} in BO/SC and 5.8 m^3 ha^{-1} in BO/SCT, compared to 5.6 m^3 ha^{-1} in the noncompacted soil (BO/VC).

Vegetation Control Effects on Tree Growth, Foliar N, and Soil Microclimate

Understory vegetation canopy cover, which was heavily dominated by herbs, was markedly greater in BO/NVC than in BO/VC (Table 2). Understory canopy cover varied between 28% in year 1 and 95% in year 5 in BO/NVC, and between 1% in year 4 and 7% in year 1 in BO/VC. We recorded 73 vascular plant species including 57 herb, 11 shrub, and 5 tree species. *Oxalis oregana*, a native herb, was the dominant species in every year in BO/NVC. It was also common in years 1–3 in BO/VC despite very low cover. *Hypochaeris radicata* L. (hairy cat's ear), an aggressive introduced perennial herb, was dominant in years 2–5 in BO/VC, and also one of the most conspicuous herbs in years 3–5 in BO/NVC.

Biomass of understory vegetation was significantly reduced by the vegetation control treatments at both ages 3 and 5 (Table 2). Understory biomass levels on vegetation control plots remained similar between ages 3 and 5 whereas levels on plots without vegetation control increased by 16% during this time period.

At year 5, mean dbh and height in BO/NVC were 34 mm and 308 cm, respectively, compared to 45 mm and 357 cm, respectively in BO/VC. Trees in BO/VC had greater mean height than those in BO/NVC in years 4 and 5 (Fig. 3A). Mean BD in BO/VC was greater than in BO/NVC in years 3–5 (Fig. 3B). Stand stem volume at year 5 was 5.6 m^3 ha^{-1} in BO/VC and 3.7 m^3 ha^{-1} in BO/NVC. At year 5, trees in BO/VC achieved 71% crown closure compared to 53% crown closure in BO/NVC ($P \leq 0.05$).

Mean foliar N concentration of trees in BO/VC was greater than that in BO/NVC in January 2003 (i.e., age 3) and in March 2004 (i.e., age 4), but they did not differ at age 5 (Table 3). There was a trend for decreasing foliar N concentration with age in BO/VC ($P = 0.01$), but N concentration did not change significantly over time in BO/NVC. There were no relevant differences in concentrations of other foliar nutrients between BO/VC and BO/NVC (data not shown).

Volumetric soil water content during the growing season at 40-cm soil depth was greater in BO/VC than in BO/NVC in years 3 and 4 (Table 4). At the 60-cm depth, volumetric soil water content was greater in BO/VC than in BO/NVC in years 3–5. Approximate soil water tensions across the BO/VC and BO/NVC treatments associated with volumetric soil water contents in m^3 m^{-3} by soil depth were: 0.34 (−300 kPa) and 0.37 (−170 kPa) at the 20-cm depth, 0.36 (−280 kPa) and 0.43 (−10 kPa) at the 40-cm depth, and 0.40 (−60 kPa) and 0.46 (−10 kPa) at the 60-cm depth.

Relative Growth Rates

Mean relative growth rate in stem diameter was greater in BO/VC than in TTP only in year 3 (0.12 ± 0.002 versus 0.11 ± 0.002, $P < 0.05$), and there were no differences between these treatments in MRGR in height in any year. Trees in BO/VC, BO/SC, and BO/SCT did not differ in MRGR either for stem diameter or height in the years for which measurements could be compared (years 4 and 5). For vegetation control treatments, MRGR in stem diameter for trees in BO/VC was greater than in BO/NVC in years 2–4, but this trend reversed in year 5 (Fig. 4). Relative growth rate in height was lower for trees in BO/NVC than for trees in BO/VC in years 3 and 4.

Second Flushing

There were no differences in frequency of second flushing among biomass-removal treatments, or soil-compaction, and soil-compaction and tillage treatments. Frequency of second flushing was lower for trees in BO/NVC than for trees in BO/VC in years 4 and 5 at 0.17 and 0.30 compared to 0.39 and 0.51, respectively ($P \leq 0.05$). For all treatments, frequency values were particularly low (range = 0.09–0.14) in year 3 when precipitation in July and August was only 14 mm. In contrast, frequency of second flushing ranged between 0.74 and 0.78 in year 2.

Discussion

Impacts of biomass-removal treatments on tree growth up to year 5 were minor despite the fact that nutrient-rich foliage and all stem and branch biomass were removed in TT and TTP, and additional nutrients in coarse woody debris were exported from the site in TTP. With regard to N, usually the most limiting nutrient for tree growth in the Pacific Northwest (Gessel et al. 1990), foliar concentrations

Table 1. Tree height and stem diameter (basal diameter, or diameter at 1.3-m height, dbh) of Douglas-fir at the end of growing seasons 3–5 in non-soil compaction (NSC), soil-compaction (SC), and soil compaction plus tillage (SCT) treatments at Fall River[1]

	Year 3			Year 4			Year 5		
	NSC	SC	SCT	NSC	SC	SCT	NSC	SC	SCT
Height (cm)	153 a	152 a	159 a	246 a	249 a	256 a	357 b	360 ab	370 a
Basal diameter (mm)	32 a	32 a	33 a	58 a	58 a	59 a	82 a	82 a	84 a
dbh (mm)	9 a	10 a	10 a	24 a	24 a	25 a	45 a	46 a	47 a

For each year and variable, values followed by the same letters do not differ at $P \leq 0.05$.
[1] All these treatments were applied on plots with bole-only removal and vegetation control.

Table 2. Understory vegetation canopy cover, biomass and composition (dominant vascular plant species) in treatments with (VC) and without vegetation control (NVC) at Fall River[1]

	Canopy cover (%)		Biomass (kg ha^{-1})		Dominant vascular plant species[2]	
Year	VC	NVC	VC	NVC	VC	NVC
1	7.0 ± 2.4 b	27.9 ± 5.2 a	—	—	Oo	Oo
2	4.9 ± 1.5 b	72.5 ± 4.6 a	—	—	Oo	Hr, Sv,Oo
3	4.5 ± 2.3 b	83.1 ± 3.9 a	75 ± 13 b	2533 ± 301 a	Oo,Hr,Ea	Oo, Hr
4	1.5 ± 0.4 b	91.2 ± 3.4 a	—	—	Hr, Oo	Hr
5	2.3 ± 0.4 b	94.6 ± 1.7 a	70 ± 21 b	2940 ± 256 a	Hr, Oo	Ea, Hr, Hl

[1] Oo = *Oxalis oregana*, Hr = *Hypochaeris radicata*, Sv = *Senecio vulgaris*, Ea = *Epilobium angustifolium*, Hl = *Holcus lanatus*. Douglas-fir seedlings were excluded.
Values are means ± one standard error. For each year and variable, values followed by the same letters do not differ at $P \leq 0.05$.
[2] Vegetation control treatments were applied on plots with bole-only removal.

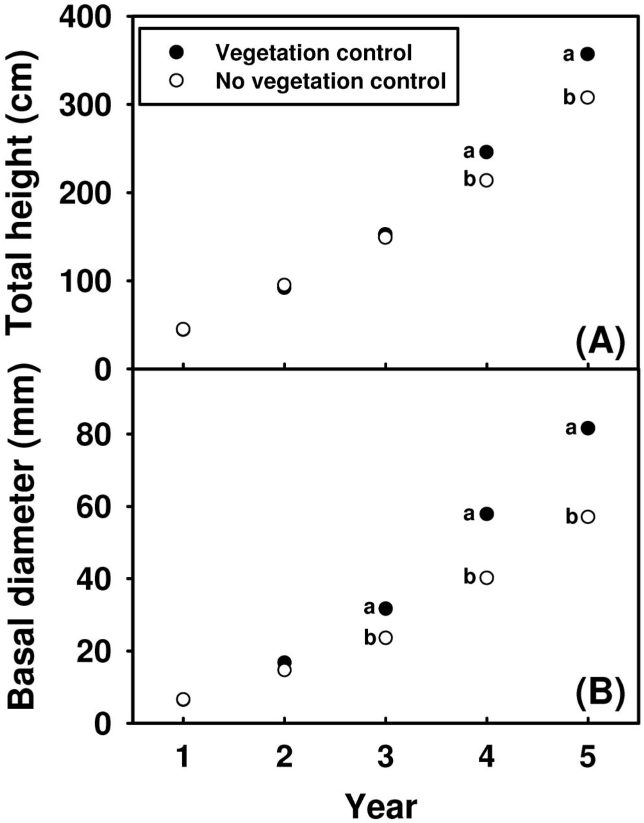

Figure 3. Mean height and stem basal diameter of Douglas-fir trees in vegetation control treatments during the first five growing seasons (years 2000 to 2004) at Fall River. Means with the same letter for a given year are not significantly different at $P \leq 0.05$.

Table 3. Percent foliar nitrogen concentrations for trees in vegetation-control treatments at Fall River[1]

Treatment	Jan. 2003 (age 3)	Mar. 2004 (age 4)	Jan. 2005 (age 5)
Vegetation control	2.30 ± 0.11 a	1.99 ± 0.10 a	1.58 ± 0.11 a
No vegetation control	1.81 ± 0.08 a	1.78 ± 0.07 b	1.59 ± 0.10 a

Values are means ± one standard error. For each sampling date, values followed by the same letters in columns do not differ at $P \leq 0.05$.
[1] Vegetation control treatments were applied on plots with bole-only removal.

Table 4. Average soil volumetric water content at 20-, 40-, and 60-cm depth in treatments with and without vegetation control during three growing seasons at Fall River[1]

Soil depth (cm)	Soil volumetric water content (m^3 m^{-3}): Vegetation control	No vegetation control
Year 3		
20	0.34 ± 0.1 a	0.34 ± 0.1 a
40	0.42 ± 0.1 a	0.36 ± 0.1 b
60	0.46 ± 0.0 a	0.40 ± 0.1 b
Year 4		
20	0.35 ± 0.1 a	0.35 ± 0.1 a
40	0.43 ± 0.1 a	0.36 ± 0.1 b
60	0.46 ± 0.0 a	0.41 ± 0.1 b
Year 5		
20	0.35 ± 0.1 a	0.37 ± 0.1 a
40	0.41 ± 0.1 a	0.39 ± 0.1 a
60	0.45 ± 0.1 a	0.43 ± 0.1 b

Values are means ± one standard error. For each year and soil depth, treatment means followed by the same letter do not differ at $P \leq 0.05$.
[1] Vegetation control treatments were applied on plots with bole-only removal.

for trees in BO and TTP did not differ in any sampling from ages 3 to 5. Nitrogen removal from the site in the most-intensive biomass-removal treatment was 940 kg ha^{-1}, which represented only 6% of the total N store of the site to the 80-cm soil depth.

It is uncertain whether the small differences in tree growth in the biomass-removal treatments (i.e., tree size slightly greater in BO than in TT) were related to treatment-caused microclimate differences rather than to differences in nutrient availability. If that was the case, greater mean stem diameter in BO than in TT could have been caused by increased soil water in BO because foliar N concentrations for trees in these treatments did not differ. During most of the second and third growing seasons, volumetric soil water was greater in BO than in TTP (Roberts et al. 2005), but these differences were not evident in years 4 and 5. At ages 4 and 5, water demand from trees may have affected surface soil water more than evaporation from the soil surface.

Long-term monitoring of biomass-removal impacts on tree growth, stand leaf area, and foliar nutrient concentration and content, will allow us to determine whether (and to what extent) nutrient limitations arise. Detrimental impacts of biomass removals on tree growth sometimes do not become apparent until several years after harvest. In Scots pine (*Pinus sylvestris* L.) growing on a moderately fertile

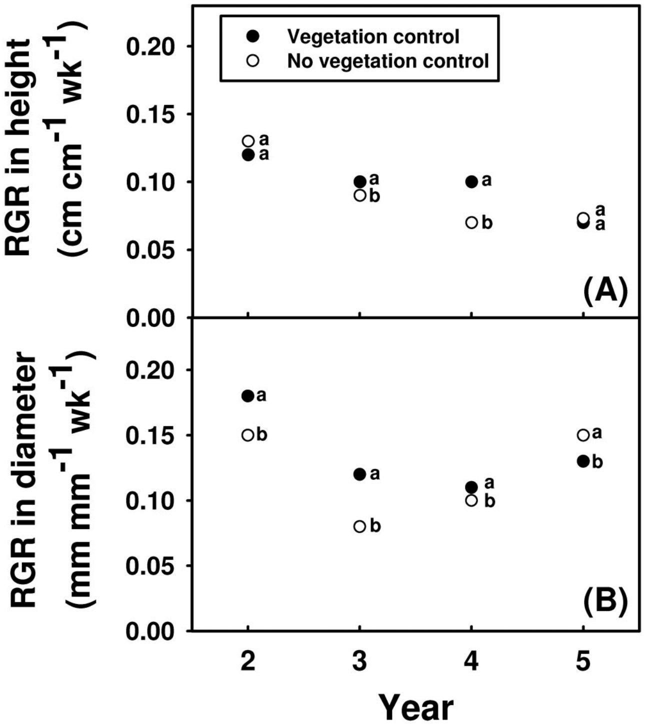

Figure 4. Relative growth rate in height and stem diameter in vegetation control treatments in years 2 to 4 at Fall River. Means with the same letter for a given year are not significantly different at $P \leq 0.05$.

orthic podzol in southern Sweden, stand basal area and wood volume became lower only 12 years after whole-tree harvest compared with conventional bole-only removal (Egnell and Valinger 2003).

Soil compaction did not negatively affect growth of Douglas-fir despite the relatively fine texture (i.e., silty clay loam to clay loam A horizon) of the Boistfort soil at Fall River. This agreed with results from previous research in coastal Washington indicating no effect of compaction on tree growth when soil disturbance did not exceed class 2 soil disturbance (i.e., churning and mixing of the topsoil with the forest floor and slash) (Miller et al. 1996). At Fall River, soil compaction increased soil bulk density in the 0–30-cm depth to a maximum of 0.82 Mg m^{-3}, and mean soil strength measured at 2-cm depth increments in the 0–60-cm depth to a maximum of 1,310 kPa (Ares et al. 2005). These maximum values were well below limiting levels for tree root growth (Greacen and Sands 1980). In microsites within ground-harvested plots, soil compaction increased growth at year 3 of trees planted on traffic lane areas with up to class 2 disturbance compared to trees in noncompacted areas (Ares et al. 2005). Increased available water in the −10 to −200 kPa range likely contributed to the increased tree growth on compacted lanes. Tillage had a positive effect on mean tree height at year 5 possibly because of improved soil environment for root growth.

Vegetation control clearly increased tree size particularly in years 4 and 5. Accordingly, an ancillary study at Fall River revealed that total aboveground tree biomass accumulation at age 5 was 12 Mg ha^{-1} in BO/VC compared to 5 Mg ha^{-1} in BO/NVC (Petersen 2005). Combining tree and understory vegetation resulted in 53% more aboveground vegetation biomass at year 5 in BO/VC than in BO/NVC. The same study indicated that stand leaf area index was 2.5 in BO/VC and 1.0 in BO/NVC.

Although foliar N concentrations were significantly greater for trees in BO/VC than for trees in BO/NVC at ages 3 and 4, N concentrations in BO/NVC (≥1.78%) were probably not low enough to limit tree growth. Critical foliar N levels for Douglas-fir has been considered to be in the 1.30–1.60% range (Walker and Gessel 1991, A. Dobkowski, Weyerhaeuser Co., personal communication, 2005), although more research is needed on variation of foliar N concentrations within the growing season, and the relationship between foliar N content (i.e., N amount per unit leaf area) and tree growth.

Considerable research in the Pacific Northwest region has demonstrated the limiting effect of both shrub and herbaceous competition on tree growth (Peterson and Newton 1985, White and Newton 1989, Chang et al. 1996, Stein 1999). Vegetation competition at Fall River was heavily dominated by herbs. Herbaceous vegetation at Fall River rapidly became dominant in BO/NVC during the first year, but was effectively controlled by herbicides in BO/VC. Although several vascular plant species were conspicuous at various times over the 5 years of the study, as many as 66 herbaceous species also contributed to a dense vegetation stratum.

Increased tree growth in BO/VC compared to BO/NVC corresponded with increased soil water at the 40- and 60-cm depths during the growing season in most years. Previous measurements revealed greater volumetric soil water content at the 0–20-cm depth in BO/VC than in BO/NVC during the second and third growing seasons (Roberts et al. 2005). Greater $\delta^{13}C$ in latewood of trees in BO/NVC than that of trees in BO/VC (data not shown) supported the hypothesis that trees in BO/NVC experienced greater water stress in the summer than trees in BO/VC because of reduced soil water availability. Also, annual diameter increment of the four trees closest to each access tube was positively correlated to soil volumetric water content at 40- and 60-cm depths in the summer of years 3 and 4 (Devine and Harrington 2006). According to the soil water potentials calculated for BO/VC and BO/NVC at Fall River, it appears that early growth of Douglas-fir begins to be limited at soil water potentials greater (less negative) than −200 kPa.

In year 5, greater MRGR of Douglas-fir trees in BO/NVC than that in BO/VC may have been caused by increased intraspecific competition in BO/VC. A similar phenomenon was noticed between ages 11 and 13 for naturally-regenerated loblolly pine that had received complete vegetation control until age 5 (Cain 1999). Trends in MRGR at Fall River suggest that the divergence in growth rates between BO/VC and BO/NVC may not continue later in stand development. The growth pattern where two treatments show an early growth rate divergence (i.e., growth curves diverge) followed by similar growth rates (i.e., growth curves parallel each other) has been described as type I response (Snowdon and Waring 1984). Thus, a type I response reduces the time needed for a stand to reach a given stage of development. Type I response was found in 13- and 14-year old *Pinus radiata* receiving vegetation control in two experiments in New Zealand (Mason and Milne 1999), where the initial growth gain caused by vegetation control was preserved at mid-rotation but not further increased.

Second flushing varied widely from year to year, and treatment differences were generally small. Trees in BO/NVC had significantly less second flushing than trees with vegetation control in years 4 and 5. To determine the cause of the large interannual variability in second flushing would require detailed microclimatic and tree measurements beyond the scope of this study. In Douglas-fir, the first flush usually includes both predetermined growth from the overwintered bud, and continuous or free growth as the apical meristem produces additional needle primordia during the growing season as long as conditions for shoot growth are favorable. If soil water becomes limiting, bud scales are formed and a terminal bud is set; if a period of favorable soil water follows, then the recently formed bud may break and a second flush occurs (Cline and Harrington 2007). The lower soil water content in BO/NVC may have contributed to reduced second flushing compared to BO/VC as the greater competition for soil water in this treatment may not have permitted budbreak. Long-term observations are needed to determine whether this translates into a greater frequency of stem and wood defects in BO/VC because the predicted faster crown closure in BO/VC may mitigate the expression of potential defects.

Conclusions

Biomass removal at harvest did not affect tree survival, foliar N concentration, or second flushing, and only slightly affected tree growth at age five. This was likely because only a small proportion of the N capital of the site was removed at harvest.

Compaction from ground-based harvesting equipment did not affect tree survival and growth, foliar N concentration, or second flushing on the Boistfort Andisol, which has inherently low bulk density, low soil strength, high soil organic matter content, and no impedance layers for root growth.

Five-year control of competing vegetation (herbs and shrubs) had far greater effect on Douglas-fir growth than did biomass removal and equipment traffic. The strong positive effect of vegetation control on tree growth points to the fact that competition for soil water (and possibly for soil N) between understory vegetation and planted trees is still a very important phenomenon in a highly productive site of Coastal Washington. One might expect that resources were sufficient for both understory plants and trees in a site with high mean annual precipitation, a soil with high water storage, and more than 13,000 kg ha^{-1} of total N in the 0–80-cm soil depth, but that may have not been not the case. Soil water limitation for tree growth caused by understory vegetation competition during the summer appeared to be the main limiting factor rather than limited N supply because foliar N concentrations were not consistently related to tree growth and did not differ for trees in BO/NVC and BO/VC in year 5. Thus, reducing understory vegetation had a more pronounced effect on soil water availability than retaining logging slash.

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