Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir seedling growth

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Abstract

Decisions made during stand regeneration that affect subsequent levels of competing vegetation and residual biomass can have important short-term consequences for early stand growth, and may affect long-term site productivity. Competing vegetation clearly affects the availability of site resources such as soil moisture and nutrients. Harvest residues can also impact the availability of site resources. We examined second- and third-year seedling performance of a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantation with different vegetation control and biomass retention treatments on a highly productive site in the coast range of Washington. Treatments included a bole-only harvest without vegetation control (BO − VC), a bole-only harvest with complete vegetation control (BO + VC), and a total tree harvest with complete vegetation control that also included removal of all coarse woody debris and harvest residues (TTP + VC). The objectives of the study were to determine if vegetation control and residue retention treatments affected soil moisture, soil temperature, and apparent nitrogen (N) availability, and whether these differences in site resources were correlated with seedling size and growth. In both the second and third growing seasons, volumetric soil moisture at 0–20 cm depth was lowest on plots that did not receive vegetation control (BO − VC). Seedlings on these plots also had the lowest diameter and volume growth. In year 2, which was fairly moist, volume growth on TTP + VC plots was slightly higher than on BO + VC plots. TTP + VC plots did have lower soil moisture, but soil temperatures were slightly warmer. In year 3, a drier year, growth was greatest on BO + VC plots, which had consistently higher soil moisture levels. Apparent N availability in year 3 also varied with vegetation control. Douglas-fir foliar N concentrations averaged 2.3% on the plots where competing vegetation was eliminated, compared to 1.8% on plots where competing vegetation was not controlled. Douglas-fir foliar N concentrations did not differ between residue retention treatments, although N concentrations of competing vegetation were higher where residual biomass was retained. Higher apparent N availability was correlated with greater seedling growth. Based on results from years 2 and 3, it appears that soil moisture, particularly late in the growing season, had the greatest effect on seedling growth in both years. Available N may also have played a role, although the effects of N cannot be completely separated from those of soil moisture. When soil moisture is adequate, it appears that available N and soil temperature exert greater influence on growth. Vegetation control and

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residue retention can influence all three of these factors. The relative importance of each factor may depend on the year-to-year variation in environmental conditions.

1. Introduction

Several decisions made at the time of a regeneration harvest can have considerable impact on the growth and development of the new stand. One decision concerns how to deal with the competing vegetation that typically develops following harvest. Competing vegetation can influence the establishment and growth of the new stand by competing with crop trees for limiting growth resources. Positive effects of vegetation control on seedling growth have been associated with increases in available moisture (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).

Another harvest and regeneration decision involves the amount of biomass removed from the site or, conversely, the amount of residual biomass retained on the site. Historically, only the commercial portion of merchantable stems was removed from the site. The non-merchantable portions of the harvested trees (branches, foliage, upper stems, etc.), along with the total biomass of non-merchantable trees, were retained on the site, although residual biomass was often burned to facilitate planting or reduce wildfire risk. Changing merchantability standards, evolving harvest technologies, and harvests coming increasingly from managed plantations are leading to changes in how trees are removed from stands. Whole-tree harvesting systems remove not only the merchantable portion of the stem, but portions of the non-merchantable components of trees as well. How much non-merchantable material is removed varies depending on the species and harvest system involved. In general, however, whole-tree harvesting systems retain less biomass on the site than traditional harvesting approaches. In addition, the amount of large woody debris retained on site is generally reduced as the age of harvested stands decreases. At least partly because of reductions in the total amount of organic residue retained following repeated harvest, as well as the size of the coarse woody debris retained, concern has been expressed about the impacts of intensive management on site productivity (Powers, 1999; Vance, 2000).

We are just beginning to understand the influence of residual biomass on site resources, seedling performance, and long-term site productivity. Whole-tree harvesting clearly removes more total nutrients from the site than conventional harvesting (Kimmins, 1977; Freedman et al., 1981; Johnson et al., 1982; Egnell and Valinger, 2003), but the significance of greater biomass removals on both short- and long-term performance of the subsequent stand is not as clear. Retention of residual biomass affects long-term soil organic matter levels, which is a key element in sustaining site productivity (Powers et al., 1990; Vance, 2000). Retention of residues can also, in some cases, conserve soil moisture (Smethurst and Nambiar, 1990; O'Connell et al., 2004), which may affect tree establishment and growth in the subsequent stand. Biomass retention can also affect nutrient dynamics, often increasing nutrient availability and potentially reducing nutrient loss from leaching (Jurgensen et al., 1992; Carlyle et al., 1998; Blumfield and Xu, 2003). Other studies, however, have indicated little or no effect of residue retention on nutrient availability (Proe and Dutch, 1994), particularly on higher quality sites (Smith et al., 2000).

The Fall River long-term site productivity study in the coast range of western Washington was established to study the impacts of forest management practices on long-term productivity of a highly productive Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site (Terry et al., 2001). Study treatments include varying levels of residual biomass retention, vegetation and nutrient management, and soil disturbance prior to planting Douglas-fir seedlings. Our objectives in this paper are to compare treatment effects within

two levels of residual biomass retention and vegetation management. Specifically, our analysis will:

a. document differences in seedling size and growth related to vegetation control and biomass retention treatments;
b. examine the relationships between seedling growth following planting and treatment differences in competing vegetation biomass and cover, soil moisture availability, and indirect indicators of nitrogen (N) availability to seedlings.

Harvesting and regeneration practices are commonly believed to potentially affect productivity of future rotations (Powers et al., 1990; Nambiar, 1996), although such effects have been difficult to document due to the lack of adequately designed trials (Smith et al., 1994). Early differences in stand development due to differences in harvesting, site preparation, and residue management treatments may be indicative of longer-term impacts on productivity. This study is an attempt to elucidate the factors that lead to differences in early stand growth on a highly productive site.

2. Methods

2.1. Site description

The study site is located on industrial forestland in Pacific County in SW Washington, approximately 60 km southwest of Olympia, WA, USA. The site is gently sloping (<10% slope) with a westerly aspect. Annual precipitation averages 2260 mm, falling mostly as rain. Summers are dry with average rainfall of only 240 mm from June to September. Mean annual temperature is 9.2 °C with an average August high of 23.1 °C and an average January low of −0.1 °C (USDA NRCS, 1999). Weather station data from the site shows that year 3 of the study had nearly average temperatures; however, precipitation for the year was only about 60% of normal, and only 112 mm of rain was recorded from June 1 to September 30.

The soil at the site is a deep, well-drained, silt-loam (A and AB horizons) to silty-clay loam (subsoil) developed from weathered basalt with considerable volcanic ash influence in the upper horizons (Steinbrenner and Gehrke, 1973). The soil is classified

as a Typic Fulvudand in the Boistfort series. Depth of the A horizon averages about 16 cm, the AB horizon is about 28 cm thick, and B horizon extends to a depth of over 150 cm. The ash influence gives these soils low bulk density and very high moisture holding capacity (Shoji et al., 1993). Organic matter is high (soil C averages 9% in the 0–20 cm depth), which contributes to the high moisture holding capacity. The soils are very productive for forest growth, with Douglas-fir site index (King, 1966) averaging 42 m at 50 years (Terry et al., 2001).

The site is located in the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) vegetation zone (Franklin and Dyrness, 1973). The predominant plant association identified pretreatment was *Tsuga heterophylla/ Polystichum munitum–Oxalis oregana* (Henderson et al., 1989). The old growth stand originally occupying the site was harvested in 1952 and 1953 using a cable logging system, followed by broadcast burning and planting of Douglas-fir. The subsequent stand was precommercially thinned in 1971, and fertilized four times between 1970 and 1995 with urea. Harvesting and implementation of treatments for the current study took place from April to July of 1999 (Terry et al., 2001).

2.2. Treatments

The Fall River study has a randomized complete block design that will ultimately include 12 treatments replicated across 4 blocks. Seven of the treatments are currently implemented. Treatments to be implemented in future years involve fertilization. The analysis reported in this paper examines three of the treatments resulting from combinations of two residue retention levels and two vegetation control levels. Because fertilization treatments have not yet been implemented, two replicates of each of the three treatments are represented in each of the four blocks, for a total of eight plots per treatment. Treatment plots are 30 m × 85 m (0.25 ha), with an internal 15 m × 70 m (0.10 ha) measurement plot. The treatments examined in this study are

- Bole-only without vegetation control (BO − VC): Only the merchantable stem portion of harvested trees (to an upper stem diameter of ca. 10 cm) was removed. All logging slash was retained and

scattered uniformly across the site. No actions were taken to control competing vegetation.

- Bole-only with vegetation control (BO + VC): Same as the BO − VC treatment, with the addition of intensive vegetation control for three growing seasons following planting. The objective of the treatment was to approach complete control of competing vegetation, and was not intended to simulate a typical operational vegetation control treatment. First-year (2000) treatment involved a broadcast application of Oust[®] (0.21 kg) and Accord Concentrate[®] (4.67 L) applied with a surfactant in a water mix at 93.5 L ha^{−1} using backpack sprayers ca. 2 weeks prior to planting. Second-year (2001) treatments included a March broadcast application of Atrazine 4L[®] (9.3 L) in water mix of 93.5 L ha^{−1}, and a directed spot-spray of Accord Concentrate[®] (0.75% by volume in water) applied to vegetation between rows in April–May. Third-year (2002) treatments included a March broadcast application of 9.3 L Atrazine 4 L[®] and 0.17 kg of Oust[®] in a water mix at 150 L ha^{−1}, a directed spot-spray application of Accord Concentrate[®] applied in June–July, and a spot-spray of 1% Transline[®] with surfactant was applied in April–May to control persistent shrub species.
- Total-tree plus residue removal with vegetation control (TTP + VC): Harvesting removed the entire tree including all attached live and dead limbs. All coarse woody debris was removed with the exception of rotted material that could not be removed intact. The larger coarse woody debris was removed mechanically using a shovel excavator positioned outside of the measurement plot. In addition, all live or dead limbs greater than 0.6 cm remaining on the plot were manually removed. Vegetation control was the same as described for the BO + VC treatment.

All harvested trees were hand-felled with chain saws. The trees on each plot were felled so that they remained within plot boundaries. Trees were removed from the plots with a cable yarder to minimize site disturbance and soil compaction. Plots were hand planted in March 2000 with Douglas-fir seedlings on a 2.5 m × 2.5 m spacing (1600 ha^{−1}). Seed source for the planting stock was a mixed lot of 23 first-generation half-sib families. Seedlings were 1 + 1 trans-

plants, graded prior to planting to reduce size variation. Root-collar diameter of planted seedlings was between 5 and 10 mm, and stem height was between 35 and 50 cm. Natural regeneration of western hemlock or other conifer tree species was manually removed from all plots. The entire study area was fenced to prevent deer and elk browsing.

Residual biomass was sampled on four plots per residue treatment (1 plot per block) in the first year following treatment. Ten 10 m line transects per plot were used to sample material less than 60 cm in diameter following the procedures of Brown (1974) and Harmon and Sexton (1996). All material on the plot 60 cm in diameter or greater was measured. Residue treatments resulted in distinctly different levels of residual slash and legacy wood retention— 133.2 and 2.5 Mg ha^{−1} on the bole-only and TTP + VC treatments, respectively. Forest floor differences were also evident, with more bare soil, scattered rotted wood, and surface mixing on the TTP + VC plots. (Data on file at the Olympia Forestry Sciences Laboratory, Olympia, WA.)

2.3. Data description

2.3.1. Tree measurements

Seedlings were measured annually following each of the first three growing seasons. Measurements included seedling height and stem diameter measured at a permanently marked location 15 cm above ground level. A seedling volume index was calculated as the product of the square of stem diameter and seedling height. Annual diameter, height, and volume growth were calculated by subtraction of the previous year's value.

2.3.2. Competing vegetation cover, biomass, and nitrogen content

Vegetation cover was assessed on each plot during July–August of each of the first three growing seasons using the general procedures of Henderson et al. (1989). A single 0.018 ha (7.5 m radius) permanent vegetation cover subplot was established within each measurement plot. An experienced plant ecologist made ocular estimates of total ground cover of all competing vascular plants. Cover estimates were made in 5% intervals for coverage above 10% and 1% intervals for coverage below 10%.

Competing vegetation was sampled for biomass and nutrient content in August 2002 (third growing season). Twenty 0.1 m^2 subplots were randomly distributed within each treatment plot outside of the permanent vegetation cover subplot. Competing vegetation was clipped at ground level and separated by woody and non-woody species. The 20 samples from each treatment plot were bulked, dried at 65 °C to a constant weight, and weighed.

The dried material was manually shredded and mixed, and a subsample was taken for nitrogen analysis. Because of the small amount of woody material (most plots had none), woody and non-woody samples were combined. Also, because of the small amount of total biomass, the two samples per block for each of the two treatments receiving vegetation control were combined for analysis of N concentration, resulting in eight samples for treatment BO − VC and four samples each for treatments BO + VC and TTP + VC. Oven-dried tissue samples were prepared for analysis by grinding to pass a 20 mesh screen. Nitrogen concentrations were determined with a LECO CNS-2000 Macro Analyzer (LECO Corp., St. Joseph, MI) at the Oregon State University Central Analytical Laboratory. Total aboveground N content of competing vegetation was estimated as the product of N concentration and competing vegetation biomass.

2.3.3. Douglas-fir foliar nitrogen concentration

Douglas-fir foliage samples were collected in February 2003 (following the third growing season) for nutrient analysis. One treatment replicate from each block (12 plots total) was selected for sampling. Stratified random samples of 15 trees per plot were selected for analysis—5 trees from each of the 3 most common forest floor conditions occurring by treatment. One branch from the uppermost whorl of the previous (2001) growing season was removed from each tree. Branches from all sides of the crowns were sampled by systematically selecting branches in different crown quadrants. In the laboratory, branches were separated into current year (2002) and previous year (2001) components. The samples were dried at 65 °C, and the foliage separated from the twigs. Foliage from the five trees sampled from each forest floor condition on each plot was composited by needle age class and a subsample of the material was prepared

for nutrient analysis. Nitrogen concentration of the Douglas-fir foliage was determined as described above. Only foliar N values for the current year foliage cohort were used in this analysis.

2.3.4. Soil moisture and temperature

Growing season soil moisture measurements were taken in years 2 and 3 on nine plots—one treatment replicate per block in three of the blocks. Measurements of volumetric soil moisture content in the top 20 cm of the soil were made using a hydrosense CS620 moisture probe with 20 cm probes (Campbell Scientific Inc., Logan, UT). In year 2, six measurements were taken at irregular intervals between mid-May and late September. In year 3, moisture readings were collected twice monthly starting in mid-May and ending in early October, for a total of 10 measurements. Twelve sampling locations were measured on each treatment plot—three locations in each of four forest floor condition classes. At each sampling location, all forest floor organic matter was temporarily cleared from an area of ca. 0.25 m^2, three to four moisture readings separated by at least 20 cm were taken, and the organic matter was replaced. Locally developed calibration curves were used to convert direct Hydrosense readings (in mV) to volumetric percent soil moisture values.

Soil temperature data was collected using HOBO H8 data loggers (Onset Computer Corp., Pocasset, MA). Soil temperature readings at 10 cm depth, averaged at 30 min intervals, were collected under different forest floor conditions at six to eight locations per plot. Soil temperature for the second growing season was available from May to July.

2.4. Analysis

A mixed-model approach (SAS 8.2, SAS Institute Inc., Cary, NC, USA) was used to test for treatment-related differences in plot mean seedling size and growth in year 3, as well as treatment effects on competing vegetation cover and biomass, nitrogen concentration of both Douglas-fir foliage and competing vegetation biomass, total N content of competing vegetation, and soil moisture. All mixed models included Block and the T × B interaction as random variables. Comparison of treatment means was made using simple *t*-tests.

A GLM procedure was used to examine correlations between year 3 seedling growth and measured site variables. The GLM procedure was also used to examine correlations among measured site variables, unless examination of scatterplots clearly showed the relationship to be nonlinear, in which case a nonlinear regression procedure was used. A critical value of $\alpha = 0.10$ was used in all statistical analyses for determining significance. This critical value was chosen to compensate for the generally lower statistical power of field studies (Peterman, 1990). Because soil moisture and plant nutrient information was not collected on all plots, it was not possible to test models examining growth as a function of multiple site variables.

As a comparison for our year 3 results, we examined seedling size and growth in year 2 and tested for treatment effects. We also tested for correlations between growth and growing season soil moisture in year 2. We did not have year 2 data on Douglas-fir foliar N concentrations or information on competing vegetation biomass or N concentration, and were therefore unable to make a complete comparison between years 2 and 3.

3. Results

3.1. Seedling size and growth by treatments

Tree size at the end of the third growing season differed by treatment. Average stem diameter and volume index on BO − VC plots were less than either of the other two treatments (Table 1). Trees on TTP + VC and BO + VC plots did not differ in diameter, but treatment BO + VC had a greater average seedling volume index. Mean seedling height did not differ among treatments, although trees on BO + VC plots were slightly taller on average than the other treatments.

Treatments also significantly affected seedling growth in year 3. Average diameter growth on BO − VC plots was less than on plots receiving vegetation control (Table 1). In addition, diameter growth on treatment BO + VC plots was greater than on TTP + VC plots. Average stem volume growth also differed among the three treatments (Table 1). Seedlings on BO + VC plots had the highest average

stem volume index growth, followed by TTP + VC and BO − VC. Average height growth on BO − VC plots was also less than on BO + VC plots, but did not differ from TTP + VC (Table 1). Mean tree size at the beginning of the growth period was a significant covariate in explaining diameter and volume growth in year 3.

There were also treatment differences in mean seedling size and growth in year 2. Average diameter and stem volume index were significantly lower on plots not receiving vegetation control (BO − VC), but did not differ between treatments BO + VC and TTP + VC (Table 1). Vegetation control also resulted in greater average diameter and volume growth in year 2. In addition, mean diameter growth on TTP + VC plots was slightly, but significantly, greater than on BO + VC plots, although average volume growth in year 2 did not differ between these two treatments.

3.2. Competing vegetation cover and biomass

Herbaceous species comprised most of the competing vegetation on all plots. Three growing seasons following planting, shrub species made up only 3.2% of the coverage and 9.3% of the biomass on the BO − VC plots. Shrub cover averaged less than 1.0% on plots receiving vegetation control, while shrub biomass averaged less than 1.4% of the total. The small shrub component included *Rubus ursinus*, *Rubus spectabilis*, *Vaccinium parvifolium* and *Sambucus racemosa*. The most common herbaceous species encountered on plots receiving no vegetation control were *Hypochaeris radicata*, *O. oregana*, *Digitalis purpurea*, *Epilobium angustifolium*, and *Holcus lanatus*. The most common herbaceous species on plots receiving vegetation control were *H. radicata*, *Disporum smithii*, *Viola sempervirens*, and *Dicentra formosa*. As expected, plots receiving no vegetation control had significantly higher vegetative cover than either of the treatments receiving vegetation control (Table 2). Total cover in year 3 averaged over 83% on the BO − VC plots. Cover on TTP + VC plots was slightly, but significantly greater than on BO + VC plots. Total biomass of competing vegetation in year 3 on BO − VC plots averaged over 2500 kg ha^{-1}— substantially greater than on plots receiving vegetation control (Table 2). Treatment TTP + VC averaged over

Table 1

Mean seedling diameter, height, and volume index following the second and third growing seasons, and mean year 2 and year 3 diameter, height, and volume index growth[a]

	Treatment (Mean (S.D.))		
	BO − VC	BO + VC	TTP + VC
Year 2			
Mean seedling size			
Stem diameter (mm)	15 (0.9) b	17 (0.8) a	17 (0.8) a
Stem height (cm)	95 (5.2) a	92 (3.8) a	93 (4.9) a
Stem volume index (cm^3)	237 (35.4) b	318 (45.9) a	316 (35.9) a
Mean seedling growth			
Diameter growth (mm year^{-1})	8 (0.6) c	10 (1.1) b	11 (0.7) a
Height growth (cm year^{-1})	49 (5.0) a	48 (3.7) a	50 (4.1) a
Volume index growth (cm^3 year^{-1})	215 (34.4) b	284 (47.2) a	292 (34.6) a
Year 3			
Mean seedling size			
Stem diameter (mm)	24 (1.5) b	32 (1.2) a	31 (1.1) a
Stem height (cm)	149 (7.9) a	152 (5.4) a	147 (5.9) a
Stem volume index (cm^3)	943 (157.0) c	1743 (145.3) a	1574 (166.4) b
Mean seedling growth			
Diameter growth (mm year^{-1})	9 (1.0) c	15 (0.4) a	14 (0.9) b
Height growth (cm year^{-1})	54 (4.2) b	60 (4.4) a	55 (4.9) b
Volume index growth (cm^3 year^{-1})	723 (137.2) c	1427 (112.3) a	1263 (139.7) b

Values within the same row followed by different letters are significantly different at $P = 0.10$.

[a] Mixed models used to test for treatment difference in mean year 3 growth included tree size at the beginning of the growth period as a covariate in the model. Determinations of significant differences based on mixed model analysis.

2.5 times more competing vegetation biomass as BO + VC, but this difference was not significant.

In year 2, competing vegetation cover on plots receiving vegetation control was similar to year 3, with average cover on TTP + VC plots again slightly, but significantly greater than on BO + VC plots (Table 2). On the BO − VC plots, average competing vegetation cover, with one less year of development, was about 10% less than in year 3, but still significantly greater than cover of the other two treatments.

3.3. Volumetric soil moisture content

Precipitation patterns during the growing season differed between years 2 and 3, resulting in somewhat different soil moisture levels and treatment response patterns. In year 3, relatively dry spring conditions

Table 2

Effects of treatment on competing vegetation cover and biomass, Douglas-fir foliar N concentration, and competing vegetation N concentration and content

	Treatment (Mean (S.D.))		
	BO − VC	BO + VC	TTP + VC
Year 2			
Competing vegetation—cover (%)	73 (13.1) a	5 (4.4) c	13 (4.1) b
Year 3			
Competing vegetation—cover (%)	83 (11.0) a	5 (6.5) c	10 (6.3) b
Competing vegetation—biomass (kg ha^{-1})	2532 (853.3) a	75 (43.3) b	196 (140.7) b
Douglas-fir foliar (%N)	1.81 (0.07) b	2.30 (0.19) a	2.28 (0.10) a
Competing vegetation (%N)	1.36 (0.12) c	2.59 (0.15) a	2.39 (0.06) b
Competing vegetation N content (kg ha^{-1})	34.1 (10.9) b	1.9 (1.2) a	4.7 (3.5) a

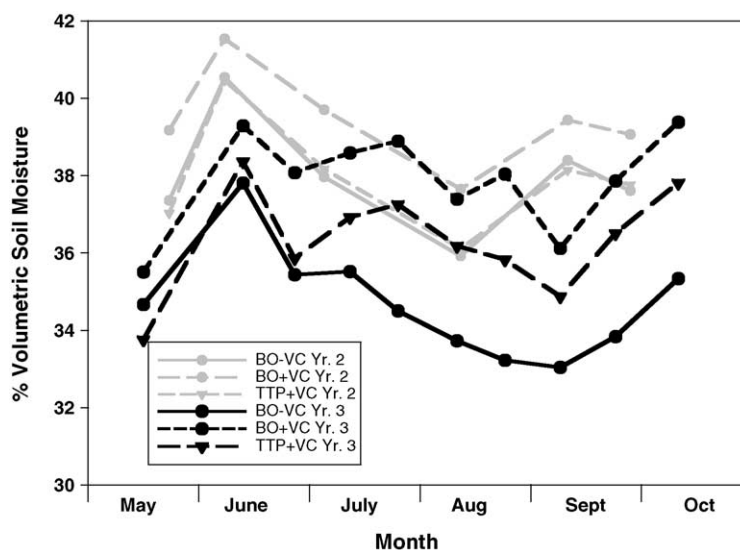Values within the same row followed by different letters are significantly different at $P = 0.10$.

Fig. 1. Percent volumetric soil moisture (top 20 cm of soil) during the growing season in year 2 (2001) and year 3 (2002) measured on plots subjected to vegetation control and biomass retention treatments. See text for treatment abbreviations. Approximate soil water tensions associated with volumetric soil moisture contents are $33\% = -137$ kPa, $35\% = -86$ kPa, $37\% = -5$ kPa, and $38\% > 1$ kPa.

resulted in lower than normal soil moistures in May. Soil moisture increased through early summer, peaking in early June (Fig. 1). Soil moisture for all treatments declined through early September, then began to increase by late-September. The site received only 14 mm of rainfall over the months of July and August in year 3.

Significant treatment differences in volumetric soil moisture (0–20 cm) during the third growing season occurred at all measurement periods except early June. Treatments BO − VC and TTP + VC did not differ in May and June, each averaging about 1.7% lower moisture content than treatment BO + VC (Fig. 1). From early July to mid-October, treatment BO − VC always had the lowest soil moisture, and BO + VC always had the highest soil moisture. Soil moisture for the period May to October differed significantly among all three treatments, averaging 34.6% (S.E. = 0.13) on BO − VC plots, 36.2% (S.E. = 0.15) on TTP + VC plots, and 37.8% (S.E. = 0.15) on BO + VC plots.

In year 2, soil moisture peaked in early June, decreased through early August, and then increased following a major precipitation event mid-August (Fig. 1). For the period May to September, soil moisture averaged 38.0% (S.E. = 0.22) on BO − VC plots, 37.9% (S.E. = 0.21) on TTP + VC plots, and

39.4% (S.E. = 0.22) on BO + VC plots. Significant treatment differences in soil moisture occurred at all six measurement periods in year 2. Treatment BO + VC always had significantly higher volumetric soil moisture than the other treatments, while treatments BO − VC and TTP + VC did not differ throughout the growing season. In nearly all cases, average soil moisture for a given treatment in year 2 was greater than in year 3 at a similar point during the growing season (Fig. 1).

Soil moisture during the third growing season was strongly and negatively correlated with both the biomass and coverage of competing vegetation on the site. This was particularly true during the last few months of the growing season. Fig. 2 demonstrates the influence that competing vegetation had on drawing down available soil moisture. Treatment BO − VC plots, with competing vegetation biomass averaging over 2500 kg ha^{-1}, averaged 2–4% lower volumetric soil moisture than the other two treatments during the period from August to mid-October.

3.4. Nitrogen

We examined three indirect indicators of plant available N in year 3: Douglas-fir foliar N concentra-
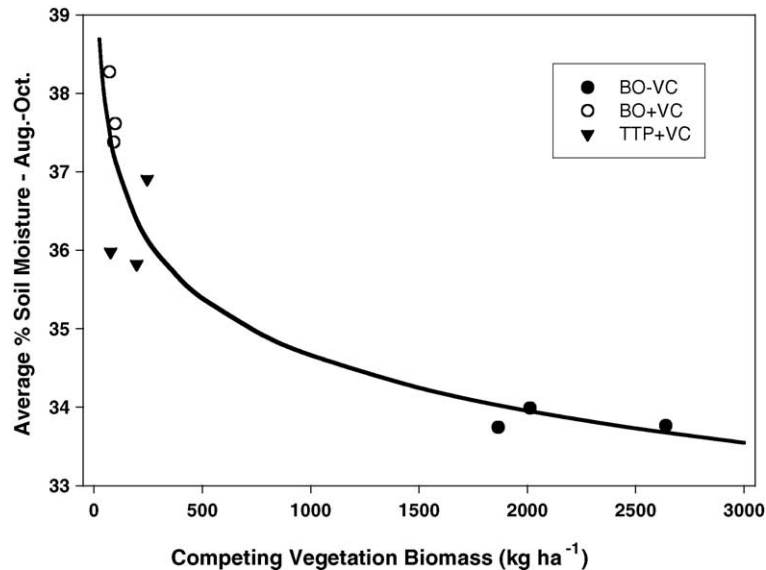
Fig. 2. Relationship between average percent volumetric soil moisture (top 20 cm of soil) from August to mid-October of year 3 and the amount of competing vegetation biomass in year 3 on plots subjected to vegetation control and biomass retention treatments.

tion, competing vegetation N concentration, and total competing vegetation N content. The N concentrations of Douglas-fir foliage and competing vegetation provide an indication of the relative amount of N that was available for plant uptake. Competing vegetation N content provides an estimate of the amount of N sequestered by the competing vegetation, and therefore not available for uptake by crop trees.

Douglas-fir foliar N concentrations were lower on BO − VC plots than on plots receiving vegetation control (Table 2). Foliar N concentrations on TTP + VC and BO + VC plots did not differ. Concentration of N in competing vegetation was also less on BO − VC plots than on the other two treatments (Table 2). In addition, N concentration of competing vegetation on the BO + VC plots was significantly greater than on TTP + VC plots. Direct treatment comparisons of competing vegetation N concentrations may be complicated by subtle differences in species composition; but it is unlikely that compositional differences were responsible for differences of over 1% between treatment BO − VC and the other two treatments.

While vegetation control treatments led to higher competing vegetation N concentrations, due to the level of vegetation present the total amount of N sequestered in competing vegetation biomass was 7–

18 times greater in the BO − VC plots (Table 2). The N content of competing vegetation on TTP + VC plots, while nearly 2.5 times greater, did not differ significantly from that on BO + VC plots.

3.5. Seedling growth correlations with competing vegetation, soil moisture, and available N

As expected, seedling growth declined with increasing levels of competition. A linear correlation explained 86% of the variation in the relationship between mean year 3 diameter growth and competing vegetation biomass. A nonlinear model best fit the relationship between year 3 stem volume growth and competing vegetation biomass (Fig. 3) explaining 82% of the variation. The relationship between year 3 height growth and competing vegetation biomass, while significant, explained only 14% of the variation in height growth. As expected, given the strong correlation between competing vegetation cover and biomass (Fig. 4), correlations between seedling performance and competing vegetation cover were similar to those with competing vegetation biomass (data not shown).

Not surprisingly, given the correlation between competing vegetation biomass and soil moisture, average third-year tree growth was highly correlated
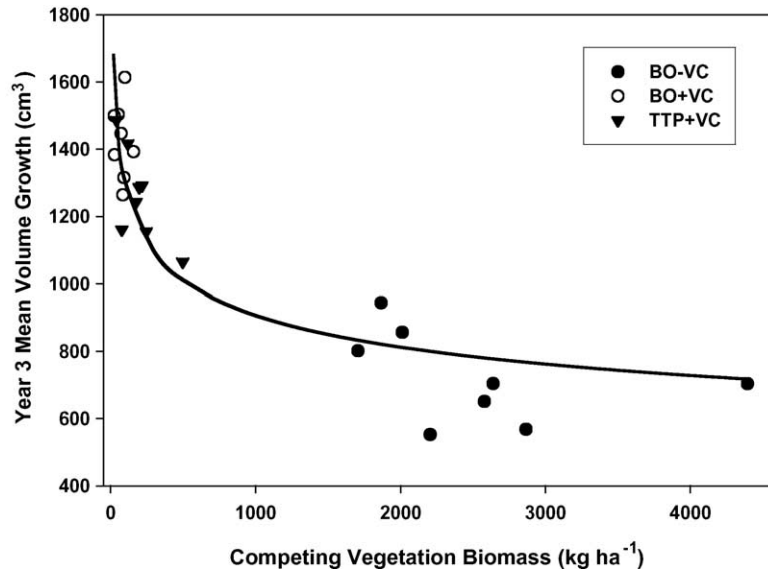
Fig. 3. Relationship between competing vegetation biomass and average seedling stem volume index growth in year 3 on plots subjected to vegetation control and biomass retention treatments. ($I_v = 2693.3\,M_c^{-0.16}$, $R^2 = 0.82$, $n = 24$, RMSE = 143.7; where I_v = year 3 volume increment (cm³) and M_c = biomass of competing vegetation (kg ha⁻¹)).

with average soil moisture, particularly late in the growing season. Mean volumetric soil moisture between July and mid-October of year 3 explained 93% of the variation in average seedling diameter growth, and 84% of the variability in average volume index growth (Fig. 5). In year 2, though there were treatment differences in soil moisture, no significant relationships existed between soil moisture and either
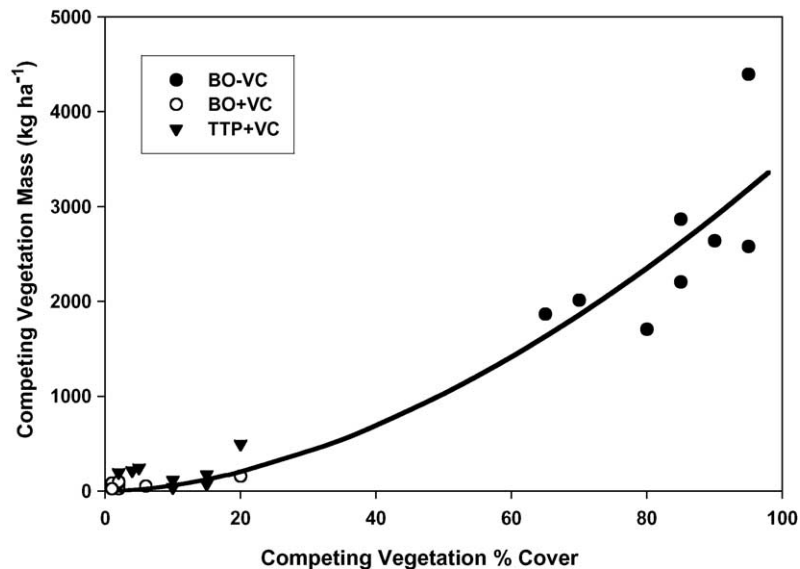

Fig. 4. Relationship between competing vegetation biomass and competing vegetation cover in year 3 on plots subjected to vegetation control and biomass retention treatments.
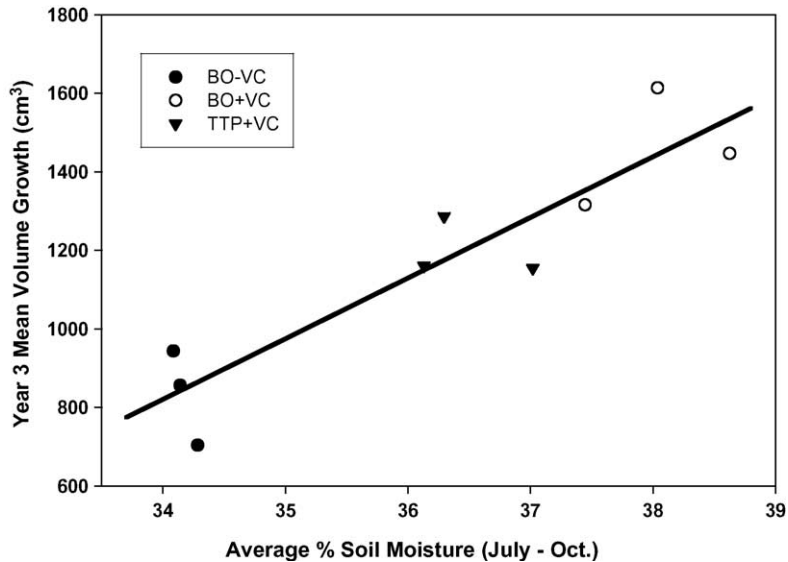
Fig. 5. Relationship between average percent volumetric soil moisture between July and August of year 3 and average seedling stem volume index growth in year 3 on plots subjected to vegetation control and biomass retention treatments ($I_v = -4430.0 + 154.4\,M_s$, $R^2 = 0.84$, $n = 9$, RMSE = 123.0; where I_v = year 3 volume index increment (cm^3) and M_s = average percent volumetric soil moisture from July to mid-October).

diameter or height growth. Late season (September) soil moisture was correlated with stem volume index growth in year 2 ($P = 0.07$), but explained only 39% of the variation in growth. Volumetric soil moisture levels were lower in year 3 (Fig. 1), and the absolute differences in soil moisture content among treatments were greater in year 3 than in year 2, suggesting that treatment effects on soil moisture were more important to growth in year 3.

Average tree growth in year 3 was also correlated with indices of N availability, with seedling growth increasing as apparent N availability increased. Nonlinear correlations existed between Douglas-fir foliar N and both mean diameter growth ($r^2 = 0.85$) and mean volume index growth ($r^2 = 0.79$) (Fig. 6).

4. Discussion

4.1. Competing vegetation

The effects of controlling competing vegetation can be examined by comparing responses between treatments BO − VC and BO + VC. Biomass of competing vegetation in year 3 on BO + VC plots averaged less than 3% of that on BO − VC plots

(Table 2), and was associated with significant differences in mean seedling growth, and therefore seedling size. Although mean heights at the end of year 3 did not differ significantly between treatments, average seedling diameter and volume index were 34% and 85% larger, respectively, under the BO + VC treatment (Table 1). Average year 3 diameter and volume index growth, when adjusted for differences in initial size, were 53% and 59% greater, respectively, under treatment BO + VC, while height growth averaged 11% greater.

Differences in seedling size and growth were associated with treatment differences in resource availability, presumably due to greater resource use by competing vegetation. Soil moisture on the BO − VC plots was lower than on the BO + VC plots throughout the third growing season. Over the late summer months (July to mid-October), when moisture is most likely to become limiting, volumetric soil moisture averaged 34% on the BO − VC plots, dropping as low as 33% in late-August/early September. During the same period soil moisture on the BO + VC plots averaged over 38% (Fig. 1). Locally developed moisture depletion curves show that over the range of soil moisture levels observed during the third growing season, soil water potentials in the top 20 cm
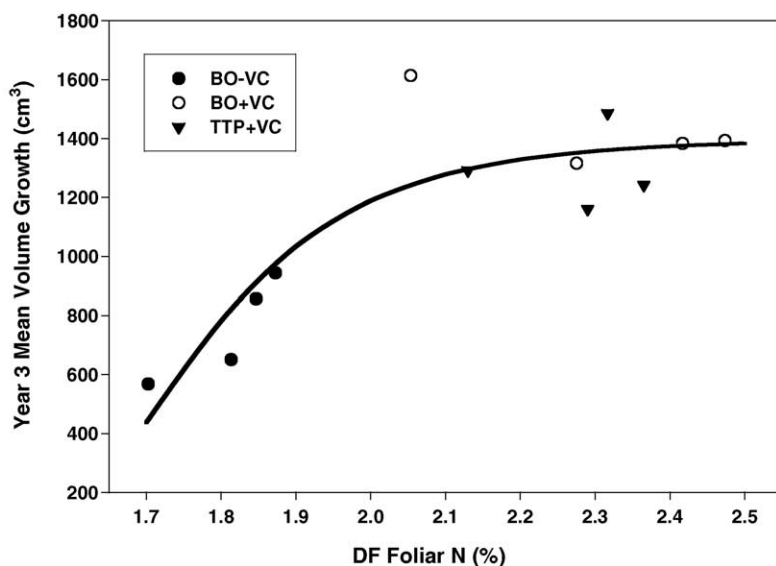
Fig. 6. Relationship between average percent foliar N concentration of Douglas-fir current-year foliage following year 3 and average seedling stem volume index growth in year 3 on plots subjected to vegetation control and biomass retention treatments ($I_v = 1398.7\,e^{-717.2(1/N^{12.1})}$, $R^2 = 0.79$, $n = 12$, RMSE = 168.9; where I_v = year 3 volume index increment (cm^3), and N = percent foliar N).

of the soil ranged from greater than -1 kPa to approximately -140 kPa. Our results suggest that Douglas-fir seedling growth is significantly reduced at relatively low levels of moisture stress. This is consistent with studies showing extensive root growth requires soil water potentials greater than -100 kPa and that seedling growth likely terminates at potentials less than -500 kPa (Glerum and Pierpoint, 1968; Spittlehouse and Childs, 1990).

While soil moisture in year 3 appeared to strongly influence seedling growth, this relationship was not nearly as strong in year 2. In year 2, as in year 3, treatment BO + VC had greater average diameter and volume index growth than treatment BO − VC, and average soil moisture on BO + VC plots was significantly greater throughout the growing season. However, soil moisture was not significantly correlated with either diameter or height growth in year 2, and volume growth was only weakly correlated with late season soil moisture. Volumetric soil moisture in year 2 averaged 1.5% greater than in year 3 on the BO + VC plots and nearly 3.5% greater than in year 3 on the BO − VC plots. More importantly, treatment differences between BO − VC and BO + VC averaged less than 1.4% in year 2 compared to an average difference of over 3.2% in year 3. Given higher overall

soil moisture and lower treatment differences, soil moisture does not appear to have been as important in explaining treatment growth differences in year 2 as in year 3.

Numerous studies have demonstrated that Douglas-fir seedlings are capable of responding positively to reductions in cover or biomass of competing vegetation (Gratkowsi and Lauterback, 1974; Preest, 1977; Dimock et al., 1983; Miller and Obermeyer, 1996; Stein, 1999). Relatively few, however, have explicitly correlated growth responses to changes in site resource availability. Of those that have, most have attributed increased growth to decreased competition for available moisture (Flint and Childs, 1987; Newton and Preest, 1988). Eissenstat and Mitchell (1983), although reporting that competing vegetation around 1-year-old Douglas-fir seedlings increased moisture stress and decreased seedling growth, suggested that other environmental factors appeared to be limiting seedling growth as well, and that seedling moisture stress may not have been the primary cause of reduced seedling growth.

Nutrient limitations commonly occur in established Douglas-fir stands throughout the Pacific Northwest (Gessel et al., 1990). However, few studies have attributed growth reductions of Douglas-fir seedlings

directly to the effects of competing vegetation on nutrient availability. In our study, concentrations of N in Douglas-fir foliage and competing vegetation biomass in the BO + VC treatment were 27% and 90% higher, respectively, than in the BO − VC treatment suggesting greater N availability. However, Douglas-fir foliar N concentrations on the BO − VC plots still averaged 1.8%, a level that most studies have suggested as adequate, if not optimal, for Douglas-fir growth (Krueger, 1967; Brix, 1981; van den Driessche, 1984; Boardman et al., 1997). Our data imply, however, that Douglas-fir seedling performance is enhanced with foliar N concentrations up to 2% or higher (Fig. 6).

Studies with other coniferous species have shown that competing vegetation can affect nutrient availability in young stands. Reduced nutrient availability, however, often occurs in conjunction with water limitations (Sutton, 1975; Elliott and White, 1987; Morris et al., 1993; Ludovici and Morris, 1997; Powers and Reynolds, 1999); and thus competing vegetation effects on nutrient availability can be difficult to separate from effects on moisture availability. Morris et al. (1993) postulated that the significance of competing vegetation effects on nutrient availability decreases as site nutrient availability increases. The growth responses associated with reduced competition observed in our study are likely, in large part, due to competition for available moisture. However, given the correlations between growth and foliar N concentrations in the Douglas-fir seedlings, increased N availability, or possibly other nutrients, appears to have been at least partly responsible for the positive growth responses that we observed.

4.2. Residual biomass

The influence of residual biomass was examined by comparing treatments BO + VC and TTP + VC. Whole tree harvesting along with removal of most woody debris (treatment TTP + VC) reduced residual biomass to approximately 2% of that remaining on the bole-only treatment plots 1 year following treatment. This reduction included removal of most of the nutrient-rich foliage from the site. Treatment differences in biomass retention did affect resource availability and tree growth; although, as has been

observed in other studies (Powers et al., 2003), the effects of residue retention were much smaller than those associated with vegetation control.

Douglas-fir foliar N concentrations at age 3 did not differ by residue retention treatment, averaging 2.3% under both TTP + VC and BO + VC. This suggests that seedlings in the two treatments had similar levels of nitrogen availability. Concentrations of N in competing vegetation biomass were slightly higher in the BO + VC treatment; however, due to greater total biomass, nearly 2.5 times more N was sequestered in competing vegetation on the TTP + VC plots. Still, the amount of N tied up in competing vegetation on TTP + VC plots was only 4.7 kg N ha^{-1}.

Removal of coarse woody debris and residual biomass resulted in lower year 3 soil moisture, presumably due to reduced ground shading and a decrease in the mulching effect. July–October volumetric soil moisture on TTP + VC plots averaged 1.5% less than on BO + VC plots (Fig. 1), about the same as the treatment differences observed in year 2. Average soil moisture for both treatments was about 1.6% lower in year 3 than in year 2.

Average seedling diameter and height at the end of year 3, while not differing significantly between treatments TTP + VC and BO + VC, were slightly higher in the bole-only treatment. Seedling volume index following year 3 did differ between the treatments, averaging nearly 11% greater in the bole-only treatment. Height growth in year 3 was 9% greater under the bole-only treatment, while diameter growth was 11% greater and volume growth was nearly 16% greater. In year 2, it is worth noting, average diameter growth on TTP + VC plots was slightly, but significantly, greater than on BO + VC plots, possibly due to more favorable overall soil moisture conditions which allowed seedlings on the TTP + VC plots to take advantage of warmer soil temperatures (Fig. 7).

Several studies have reported that harvest residue retention has, as in our study, resulted in increased soil moisture (Smethurst and Nambiar, 1990; Blumfield and Xu, 2003; O'Connell et al., 2004). We also observed warmer surface soil temperatures (10 cm depth) during the growing season where residues were removed (Fig. 7). Residue retention has been found to result in cooler soil temperatures in other studies as
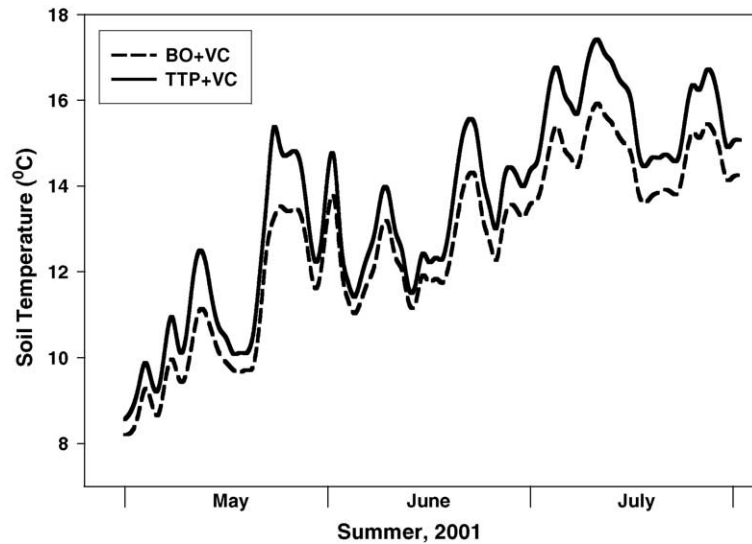
Fig. 7. Average soil temperature (10 cm depth) during May–July of growing season 2 (2001) on plots subjected to vegetation control and biomass retention treatments.

well (Valentine, 1975; Smethurst and Nambiar, 1990; Powers, 2002). In addition, residue removal exposes soils to greater soil temperature extremes and diurnal temperature variation (O'Connell et al., 2004).

Findings on the influence of harvest residue retention on nutrient dynamics have been more variable. Some studies have shown little or no impact of residue retention on available nutrients (Proe and Dutch, 1994; Smith et al., 1994); while other studies have shown nutrient related effects from residue retention. O'Connell et al. (2004) found residue retention in *Eucalyptus* plantations resulted in higher N-mineralization rates, but overall impact on soil nutrient pools over 4 years was minor (Mendham et al., 2003), suggesting greater immobilization of N on these sites. The authors suggest that residues may help conserve N for long-term availability, but may cause N limitations during the first few years of the rotation. Jurgensen et al. (1992) also found retention of harvest residues increased N-fixation rates on conifer sites in the northern Rocky Mountains. Smethurst and Nambiar (1990) found higher first-year N-mineralization rates in a young *Pinus radiata* D. Don stand where harvest residues were removed, presumably due to warmer soil temps; but rates dropped in subsequent years due to depletion of the mineralizable substrate. Blumfield and Xu (2003) reported that retention of

residues resulted in reduced net N-mineralization for 2 years following harvest, but also reduced N loss from leaching. These authors again suggest that immobilization in harvest residues may be important for N conservation.

In related investigations at the study site, data collected between March and June of the first growing season (2000) from the BO + VC and TTP + VC treatments showed net organic N in the forest floor increasing by 18% in the BO + VC treatment while decreasing by 8% in the TTP + VC treatment (Flaming, 2001). The concentration of N present in soil solution collected from lysimeters at 0.2 m depth decreased with increased slash retention (Flaming, 2001). From the end of the first growing season through the middle of the second, net N-mineralization in the forest floor and top 20 cm of soil varied only slightly between the BO + VC and TTP + VC treatments (65 and 50 kg N ha^{-1} year^{-1}, respectively) (Licata, 2004). Lysimeter collections from 1 m depth taken during the third growing season show consistently higher soil solution N concentrations on BO + VC plots compared to TTP + VC plots (personal communication with Rob Harrison and Brian Strahm, University of Washington). Thus, it appears that N availability was decreased during the first growing season due to slash retention, but by the third year

there was greater available N where slash was retained. However, observed differences in net N-mineralization and soil solution N from ages 1 to 3 were apparently not great enough to influence foliar N values between the BO + VC and TTP + VC treatments (Fig. 6).

Growth responses for a variety of species to residue retention treatments have also been variable. Several studies have reported no significant effect of residue retention on tree growth (Smethurst and Nambiar, 1990; Jones et al., 1999; Zabowski et al., 2000). Studies finding significant growth effects associated with residue retention often report growth reductions associated with whole-tree harvesting or complete residue removal (Nzila et al., 2002; Proe and Dutch, 1994). Smith et al. (1994) found no differences in age 5 heights related to residue retention treatments, but reported diameter growth reductions associated with whole-tree harvesting combined with complete forest floor removal. Mendham et al. (2003) found that retaining residues improved seedling growth only on a poor site, and only then with a doubling of harvest residues. Egnell and Valinger (2003) showed 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. Diameter growth differences between whole-tree harvesting and conventional harvesting were not significant until year 12, reduced height did not show up until age 24, and significant reductions in standing basal area ($m^2\,ha^{-1}$) were not significant until age 15. Egnell and Valinger's (2003) study illustrates the dangers associated with interpreting early, short-term treatment responses to residue retention experiments.

4.3. Conclusions

The benefits to tree growth of controlling competing vegetation, especially in young seedlings, are well established. In the present study, seedlings in the vegetation control treatments had access to greater amounts of soil moisture and available N leading to better growth. Douglas-fir foliar N concentrations were substantially higher under the vegetation control treatments, although foliar N on the BO − VC plots (1.8%) was still equal to or greater than values suggested in the literature to indicate nitrogen sufficiency. We suspect that greater growing season soil moisture on the

BO + VC plots was the primary reason vegetation control influenced year 3 tree growth in this drier than average year; however, greater N availability also appears to have had an effect on growth.

Potential benefits of harvest residue retention are less well understood. Microbial decomposition of woody debris with high C:N ratios can immobilize nutrients making them unavailable for tree growth early in the rotation. However, nutrient rich crown and foliar biomass retained on site may also represent a significant source of N for establishing seedlings. Residue treatments did not affect Douglas-fir foliar N, although the competing vegetation on the bole-only plots (BO + VC) had slightly higher N concentrations than on the TTP + VC plots. Our results suggest that the effect of residue retention on seedling performance at age 3, while possibly influenced by small differences in available N, was due mostly to greater soil moisture. While woody residues intercept small amounts of precipitation, thus preventing the moisture from reaching the soil, they also shade the soil surface and act as a mulch, lowering surface soil temperatures and reducing moisture loss from direct evaporation (Powers, 2002). Inherently high levels of soil organic matter and soil moisture holding capacity on the highly productive site used in this study may have reduced the effect of residue retention on seedling growth relative to what may have occurred on a drier or less productive site.

Both vegetation control and residue retention treatments led to increased third-year seedling growth in this study, apparently due to increases in the availability of site resources. Increased seedling performance appears to be due to increases in soil moisture, particularly late in the growing season when stem diameter growth is actively occurring and plant moisture stress is most likely to occur, and to increases in the apparent availability of N. Comparisons between years 2 and 3 seedling performances suggest that treatment effects may vary from year-to-year depending on environmental conditions, and possibly stage of seedling development. In year 2, with soil moisture less limiting, warmer soil temperatures may have been responsible for greater diameter growth on the TTP + VC plots. In year 3, however, soil moisture limitations late in the growing season resulted in greater growth for treatments that conserved moisture. This illustrates how multiple factors interact to

influence seedling performance, and how caution must be exercised in drawing conclusions from analysis of a single year's results.

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