Forest Ecology and Management 262 (2011) 586–597

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Comparison of 5th- and 14th-year Douglas-fir and understory vegetation responses to selective vegetation removal

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ARTICLE INFO

Article history:
Received 17 January 2011
Received in revised form 9 April 2011
Accepted 11 April 2011
Available online 6 May 2011

Keywords:
Understory vegetation
Vegetation competition
Tree growth
Forest productivity
Leaf area
Nitrogen resources

ABSTRACT

The effects of early vegetation management on the survival and growth of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] were examined 5 and 15 years after planting in the Oregon Coast Range. Our first objective was to document the effects of vegetation species competition upon key ecosystem properties. The second objective was to document the effects of vegetation removal during early Douglas-fir stand establishment upon long-term tree growth and on biomass production by vegetation components. Seven levels of manual vegetation removal were maintained for the first 5 years after planting: 0%, 25%, 50%, 75%, and 100% shrub removal; and 100% shrub removal combined with 50% or 100% herbaceous vegetation removal. Shrub and herb removal did not affect Douglas-fir survival at year five, but treatments providing less than 75% shrub removal significantly reduced Douglas-fir survival by year 15. Removing shrubs and herbs completely (100S + 100H) during the 5 years following tree planting allowed successful tree establishment, with a 366% increase in biomass accumulation per hectare for Douglas-fir in that treatment at the end of 14 years of growth. At 15 years stand age, even with shrub removal alone, a 304% gain in tree biomass per hectare was obtained compared to no vegetation removal (NVR). By stand age 15 years, any increase in the degree of understory removal beyond 75% did not contribute significantly to additional tree survival and growth. The understory vegetation on NVR treatment plots and the herbaceous vegetation on 100% shrub removal (100S) treatment plots, contained >90% and >80% of aboveground biomass N at 5 years, respectively, indicating possible competition for soil N. Soil moisture was not different among treatments at 5 years. Complete vegetation removal (100S + 100H) for 5 years resulted in a significant increase in soil bulk density ($P < 0.05$), a significant decrease in total soil C ($P < 0.05$) and no change in total soil N in the upper 15 cm of the mineral soil. By 14 years, however, only the soil bulk density remained greater ($P < 0.05$) on the 100S + 100H treatment. We conclude that greater tree survival and growth occurred with at least 75% shrub removal. Our results suggest that managers may have substantial flexibility in maintaining a partial understory component suitable for ecosystem productivity, canopy cover and wildlife habitat, while maintaining forests productive for timber resources.

1. Introduction

Management of early successional vegetation is important for the success of Douglas-fir plantations in the Pacific Northwest (Wagner et al., 2004; Tappeiner et al., 2007) and has become a routine silvicultural practice (Wagner et al., 2006). Interspecific competition for light, moisture, and nutrients between planted seedlings and surrounding vegetation is believed to be a principal factor affecting the growth and survival of young Douglas-fir plantations (Shainsky and Radosevich, 1992; Harrington, 2006; Tappeiner et al., 2007; Ares et al., 2007, 2008; Zhang et al., 2008; Dinger and Rose, 2009). Early reductions in stand growth associated with competing vegetation are known to reduce long-term growth and yield (Wagner et al., 2004, 2006; Wagner and Robinson, 2006; Newton and Cole, 2008; Harrington and Tappeiner, 2009; Maguire et al., 2009). Forest ecosystem research also indicates that understory retention can increase soil carbon (C) and nitrogen (N), as well as improve long-term tree growth (Busse et al., 1996.) Studies of different forests in other countries also have shown that controlling competing vegetation is essential for successful establishment of forests being managed for timber and for other resources

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doi:10.1016/j.foreco.2011.04.015

(Sternberg et al., 2001; Picon-Cochard et al., 2006; Yildiz and Eşen, 2006; Yildiz et al., 2007; Pitt et al., 2010).

Salmonberry (*Rubus spectabilis* Pursh) is a dominant shrub in the Oregon Coast Range that can fully occupy newly disturbed sites and inhibit the establishment of other plant species (Tappeiner et al., 1991, 2001). Thus, during stand initiation, treatments are applied to release conifer seedlings from competition with salmonberry and other shrubs until seedlings overtop shrubs during the stem exclusion stage (Tappeiner et al., 2007). Early successional vegetation can affect ecosystem processes in a variety of ways. For example, a dense network of salmonberry rhizomes contributes to soil stability, since these rhizomes can occur at depths of 1–2 m on steep slopes greater than 50% (Tappeiner et al., 1991). Shrub removal from a site may weaken root networks that hold the soil mantle together until a cover of trees occurs. Root networks can make the mantle two to three times stronger than those lacking them (Waring, 1986). Shrub canopies help to provide soil protection, in conjunction with canopy cover, from erosion processes (Keim and Skaugset, 2003; Keim et al., 2006).

Ecosystem productivity and nutrient retention generally increase with interspecific differences in resource requirements (Kimmins, 2004). Cole and Newton (1986) examined the effects of grass and red alder (*Alnus rubra* Bong.) competition with Douglas-fir seedlings in three Oregon Coast Range plantations. Presence of a grass understory was associated with a significant increase in phosphorus (P) concentration in five-year-old Douglas-fir foliage (0.133% P without grass vs. 0.143% P with grass). Thus, a mixture of species (e.g., when shrubs and herbs are part of the ecosystem) may provide better utilization of improved site resources.

The importance of understory vegetation in forest ecosystems may far exceed the biomass it represents, by increasing soil C and N resources for long-term tree growth (Busse et al., 1996). Management practices that reduce cover of these pioneering plants can lead to increased nutrient losses, may reduce ecological diversity, and possibly may affect sustainability (Radosevich et al., 2007; Perry et al., 2008). The implication for tree growth of retaining or removing the understory is to maintain a balance between the understory's detrimental effect through competition and its beneficial effects on soil fertility and ecosystem biodiversity (Ares et al., 2010). Such issues are relevant to current discussions concerning the need to maintain forest ecosystem productivity (Fisher and Binkley, 2000; Wagner et al., 2004, 2006; Waring and Running, 2007; Campbell et al., 2009), while promoting ecosystem sustainability (Fox, 2000; Kimmins, 2004; Balandier et al., 2006; Radosevich et al., 2007). The objectives were to document: (1) changes in ecosystem properties through manipulation of understory vegetative species composition, and (2) residual effects of vegetation removal during the early years of stand establishment on the long-term growth of trees and understory vegetation components.

We used measurements at stand ages five and 15 years from a competition experiment employing seven vegetation removal treatments in the central Oregon Coast Range (Wagner and Radosevich, 1998) to compare differences in Douglas-fir survival, growth, and biomass productivity. We tested the following hypotheses: (1) Douglas-fir survival, growth, biomass and stem volume would be lower after 14 growing seasons with no control of competing vegetation, and total aboveground ecosystem biomass also would be lower in the absence of understory vegetation control. (2) Greater aboveground N accumulation by competing vegetation would occur during the first 5 years of stand establishment compared to the subsequent 9 years. (3) Tree leaf area and leaf area index would be greater after 14 years on those treatments having greater removal of competing vegetation. (4) Tree height and diameter would be greater after 14 years where competing vegetation was substantially reduced. (5) Specific leaf area for trees would not differ after 14 years. (6) Foliar N concentrations would be greater after 14 years where competing vegetation was reduced. (7) Stable isotope patterns for $\delta^{13}C$ in tree foliage and in understory plants would show evidence for greater vegetation competition for moisture after 14 years. (8) The $\delta^{15}N$ of tree foliage and in competing vegetation would not change after 14 years due to changes in competition for soil N. (9) Soil C, N and soil bulk density would not be affected by differences in vegetation removal treatments.

2. Materials and methods

2.1. Study sites

The study sites were selected based on vegetation zones and topographic aspect. Two vegetation zones were used: a Sitka spruce [*Picea sitchensis* (Bong.) Carr.] zone that stretches along a narrow band parallel to the Pacific Ocean, and a western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] zone situated several kilometers further inland (Franklin and Dyrness, 1973). The two spruce zone sites are situated about 11 km east of the Pacific Ocean near Lincoln City, Oregon (Erickson-Round site: 44°57′N, 123°52′W, south-facing; Minski-Bald site: 44°58′N, 123°50′W, north-facing). South- and north-facing spruce zone sites are located at 230 and 380 m elevation, respectively. The two hemlock zone sites are located ~19 km east of the Pacific Ocean near Waldport, Oregon and at ~400 m elevation (Tidewater site: 44°24′N, 123°50′W, south-facing; Cannibal site: 44°22′N, 123°53′W, north-facing) (Wagner and Radosevich, 1998; Yildiz, 2000).

The spruce zone sites were clear-cut in 1983 (2 years before planting), but not burned. The north-facing site in the hemlock zone was clear-cut and then subjected to a low intensity prescribed burn in 1978. The south-facing site was clear-cut in 1971 and unsuccessfully regenerated until the experiment commenced.

Both vegetation zones have a mild, wet, maritime climate with more than 180 cm average annual precipitation, most of which occurs during November through May. The climate in the spruce zone is characterized by more summer fog and less variation in precipitation and temperature than in the hemlock zone. Both zones have mild, wet winters and relatively warm, dry summers typically extending through July and late September; the growing season is characterized by 15–20 °C daytime average temperature. The coast is influenced by a maritime climate and narrow seasonal temperature fluctuations, and freezing temperatures are rare. Summers are under the influence of the east Pacific Subtropical High, and are cool and relatively dry (Waring and Franklin, 1979). During drier years, the shallow roots of some herbs, shrubs, and tree seedlings, for example, could experience increased moisture stress, with increased competition for soil moisture.

Soils in these two zones are 1–2 m deep, relatively fertile, and well drained. They are derived from Flournoy sandstone, and are high in soil C and N, but may be low in S (Cromack et al., 1999; Perakis et al., 2006). They have a low bulk density (0.5–0.6 g cm^{-3}) and are highly porous (>20 cm h^{-1} permeability), resulting in a highly permeable soil profile that maintains generally aerobic conditions that favor rapid organic matter turnover and nutrient release (Wagner, 1989). The abundant annual rainfall and deep soil developed from sandstone in these zones provide a substantial available soil water resource for these coastal forests (Waring and Franklin, 1979; Wagner, 1989). Soils in the spruce zone are classified as Typic Haplumbrept. Hemlock zone soils are classified as Pachic Haplumbrept.

2.2. Experimental design

This study used a previously established experiment where early successional vegetation was controlled systematically around

planted Douglas-fir seedlings for 5 years (Wagner and Radosevich, 1998). The experiment used a randomized block design with four blocks (the four sites). Selection of the four blocks was based upon use of four different clear-cuts at the different block locations, as listed above, that were uniformly colonized by salmonberry (*R. spectabilis* Pursh) patches that were large enough to establish seven experimental plots for each of the randomized blocks. Each block was divided into seven 20 × 20 m plots. Treatments included seven randomly assigned levels of shrub and herbaceous vegetation removal for the first 5 years after planting Douglas-fir. The treatments included no vegetation removal (NVR); 25% (25S), 50% (50S), 75% (75S), and 100% (100S) shrub removal; 100% shrub removal + 50% herb removal (100S + 50H); and 100% shrub removal + 100% herb removal (100S + 100H).

In March, 1985, all shrubs were cleared by hand and chainsaw. During April, Douglas-fir seedlings (2–0 bare-root stock) averaging 30 cm in height, were planted at 3 × 3 m spacing (Wagner, 1989). The vegetation treatments were maintained during each growing season (April–September) from 1985 through 1989. To achieve partial vegetation removal targets, shrubs and herbaceous vegetation were removed in 2 m wide corridors that were located randomly within each plot. Herbaceous vegetation invaded each year and occupied areas from which shrubs had been removed.

The dominant shrub species on the experimental blocks included salmonberry, thimbleberry (*Rubus parviflorus* Nutt.), red elderberry [*Sambucus racemosa* L. var. *arborescens* (T. & Gray)], vine maple (*Acer circinatum* Pursh), cascara (*Rhamnus purshiana* DC.), red huckleberry (*Vaccinium parvifolium* Smith), and bitter cherry (*Prunus emarginata* Dougl.). The most abundant herbaceous species was velvetgrass (*Holcus lanatus* L.), with lesser amounts of swordfern [*Polystichum munitum* (Kaulf.) Presl.], pearly everlasting [*Anaphalis margaritacea* (L.) B. & H.], foxglove (*Digitalis purpurea* L.) and woodland groundsel (*Senecio sylvaticus* L.).

To minimize deer, elk and rodent damage, each experimental block was surrounded by a 2.5 m high, woven wire fence. After planting, each Douglas-fir seedling was further protected with a cylindrical, open-top chicken-wire cage (Wagner, 1989; Wagner and Radosevich, 1998).

2.3. Variables measured

Tree height, length of longest branches perpendicular to the tree trunk, and height to live crown were measured using a telescopic measuring pole on each Douglas-fir before bud break in the spring of 1990 and in the spring of 1999, after five and fourteen growing seasons, respectively. Trunk diameter at breast height (137 cm) (DBH) and stem diameter at 10 cm above the soil surface (DST) (only for 1990) were measured. Using equations developed by Helgerson et al. (1988), aboveground biomass of each Douglas-fir (leaf, branch, and bole) was estimated using DST in 1990; and using DBH in 1999.

Stem volume for 5-year Douglas-fir was calculated by assuming that each stem was a cone. For each tree, the DST diameter at 10 cm above the soil surface and the measured tree height were used for the calculation, as done in recent work (Pitt et al., 2010). For the 14-year stem volume calculation, the DBH at 137 cm and tree height above 137 cm (DBH) were used in the cone calculation. Tree stem volume from 15 to 137 cm was calculated as a cylinder and added to the stem volume calculated above DBH. We assumed the same stem diameter for the 14-year trees at 15 cm above the ground surface as measured at DBH, since the 15 cm measurements were not taken. We recognize that this is a less precise volume estimate for the lower stem section than was done in recent work (Maguire et al., 2009).

Increment core samples from Douglas-fir trees were taken during summer of 1999 from nine randomly chosen trees per plot. Using DBH, bark thickness and heartwood diameters, the sapwood area of each stem cross-section was calculated. Douglas-fir leaf area per tree was estimated from sapwood area using the coefficient of leaf area:sapwood ratio developed for the same species (Waring et al., 1982; Waring and Running, 2007). During the summers of 1989 and 1999, needles from 15 randomly chosen trees per plot were collected to estimate Douglas-fir SLAs (Waring and Running, 2007). The projected surface area of a needle was determined using a video image recorder and AgVision software (Decagon Devices, Inc., Pullman, Washington). In summer 1999, light interception by the canopy was estimated using a sunfleck ceptometer (Decagon Devices, Inc., Pullman, Washington). To determine the incoming photosynthetically active solar radiation (PAR) above the canopy, 10 readings were recorded in the open, then 100 readings were recorded on each block using 10 regularly spaced transects. Along each transect, 10 points were chosen randomly and used for PAR measurements. Readings were taken under the tree canopy at 15 cm above the ground between 11 am and 1 pm during several clear days in August, 1999.

For 1989, shrub and herb biomass samples, and Douglas-fir foliage samples were collected only on three treatment plots: NVR, 100S, and 100S + 100H. There was no competing vegetation remaining on the 100S + 100H plots due to 5 years of competing vegetation control. For 1999, understory vegetation biomass samples were collected from all treatments except 100S + 50H and 100S + 100H. The sparse understory remaining on these treatments was estimated subjectively from field observations and subsequent examination of some plot photographs to be only about 2–4 kg on each plot.

For both summers of 1989 and 1999, total aboveground shrub biomass was collected by cutting all shrub stems starting at ground level on two randomly located 9 m^2 areas on each experimental unit (plot) sampled. Shrub branches and leaves were separated, weighed using a calibrated field scale, and fresh weights recorded in the field for each sample area. Representative shrub component subsamples from field collected, freshly weighed shrub components, approximately 1–1.5 kg each, were taken to the laboratory. Then, fresh weights were recorded and the samples were dried in a forced-air oven at 70 °C for 48 h. This permitted fresh weight to dry weight conversions for each oven-dried sample. Herbaceous vegetation was sampled on five randomly located 1 m^2 circular areas on each experimental unit by clipping all herb aboveground biomass within each area. Herb fresh weights were recorded in the field for each sample area. Similar laboratory procedures were followed for herb samples of about 500 g fresh weight, in order to obtain fresh weight to dry weight conversions. Where herb samples were small, all the herb sample material collected was brought back from each plot to the laboratory. Total shrub and herb dry biomass (kg ha^{-1}) were calculated after oven drying samples at 70 °C for 48 h.

Dried shrub and herb samples were coarse ground in large grinding mills with a 2 mm mesh screen. Small, 1–2 g sub-samples were taken from well mixed, coarsely ground samples and processed through a small Wiley mill with a fine mesh screen. Each shrub and herb biomass sample was sub-sampled to determine its moisture content and its concentrations of C, N, $\delta^{13}C$ and $\delta^{15}N$.

For soil and root sampling to 15 cm soil depth, duplicate soil cores (7.5 cm diameter × 7.5 cm depth) were collected using a double-cylinder sliding-hammer core sampler (Blake and Hartge, 1986). In late July of 1989, soil cores were collected within each of the five 1 m^2 circular areas used for herb biomass sampling on NVR and 100S treatment plots. To sample the lower half of the 15 cm soil depth, the 7.5 cm long corer was offset at a distance of one or two core diameters. Soil core samples also were collected at five random locations within the 100S + 100H plots, which contained only Douglas-fir trees. Root cores were weighed, air-dried,

then sieved through a <2 mm mesh screen. The roots retained by this screen were hand separated from residual soil, rinsed to remove soil, and oven-dried at 70 °C for 48 h before being weighed for root biomass estimates.

Subsamples of about 50 g were taken from each 330 cm^3 field-collected soil core and placed into soil cans for soil moisture determination by drying at 105 °C for 48 h. Whole soil bulk density was determined on the same oven dry weight basis from the sliding hammer bulk density cores remaining from the original core sample before sieving to <2 mm (Blake and Hartge, 1986). Additional approximately 10–20 g subsamples were taken from the <2 mm size fraction from each core, air-dried, finely ground to a powder in a heavy duty rock grinder, and then analyzed for total C and N.

In late July of 1999, soil cores of the same size and depth were collected from each treatment plot as above (NVR, 100S, and 100S + 100H). One set of duplicate soil cores was sieved, then air-dried before roots were separated. Roots were hand separated, rinsed to remove soil, dried at 70 °C, and weighed. Total soil C and N for the <2 mm size fraction were determined as above. Whole soil bulk density was determined as above from the soil cores before sieving.

The stable isotopes, $\delta^{13}C$ and $\delta^{15}N$, have become useful tools for interpreting effects of forest understory vegetation in nutrient cycling and in competition for light and soil moisture (Staples et al., 2001; Picon-Cochard et al., 2006; Hobbie et al., 2009). Needle, shrub and herb samples were analyzed for their ^{13}C and ^{15}N stable isotope values using a continuous flow method and a Finnigan Delta Isotope Ratio Mass Spectrometer with ±0.2‰ sensitivity for both C and N. Needles were dried at 70 °C, finely ground, and analyzed for total N using a Carlo-Erba CHN Analyzer (Sparks et al., 1996). Shrub and herb tissue samples were dried at 70 °C, finely ground and analyzed for total N after digestion by micro-Kjeldahl (Sparks et al., 1996). The finely ground soil core subsamples from the <2 mm mineral soil fraction were dried at 80 °C, weighed, and analyzed for total C and N using a Carlo-Erba CHN Analyzer (Sparks et al., 1996). The N content of Douglas-fir boles and branches was estimated for the 5-year-old samples using N concentrations given for a western Washington site (Petersen et al., 2008), and for the 14-year-old samples using N concentration data from a 22-year-old Douglas-fir plantation growing on a similar site in western Washington (Cole and Rapp, 1981).

2.4. Statistical analysis

The differences among treatments for the following variables: Douglas-fir (height, DBH, volume, biomass, N, and SLA), competing vegetation (biomass and N), soil (bulk density, C, and N), total ecosystem (live biomass and N), and Douglas-fir survival, were tested with an ANOVA for a randomized block design. For each ANOVA, we used mean values for each experimental unit (plot). There were seven plots for each of the four blocks. Tukey's HSD test with $\alpha = 0.05$ was performed to permit a separation of means. Version 7.0 was used for all statistical analyses (SAS Institute, 1996). Results were considered significant at $P < 0.05$. For the stable isotopes, $\delta^{13}C$ and $\delta^{15}N$, results were considered significant at $P < 0.1$.

3. Results

3.1. Douglas-fir survival and growth

At the end of the fifth growing season in 1989, overall Douglas-fir survival was about 93% and no difference was found among the vegetation treatments (Wagner and Radosevich, 1998). After 14 years of growth, however, survival differences emerged by treatment and vegetation zone (Table 1). Douglas-fir survival declined significantly when shrub removal was less than 75% ($P = 0.034$). Even though the current study was not designed to test it, we found significant block differences ($P = 0.002$) and higher survival rates on the coastal spruce zone blocks (84–94%) than on the interior hemlock zone blocks (70–71%), implying a possible zone difference. On average, 60% of the trees survived on NVR plots, with a mean survival of 90% on 100S plots and 89% on 100S + 100H plots (Table 1). Overall mean survival among treatments and zones was 80%.

At 5 years, Douglas-fir growing with all other vegetation removed (100S + 100H) were 1.8 times taller ($P = 0.001$) and had stem diameters 3.7 times larger ($P = 0.0001$) than trees on the NVR treatments (Table 2, Fig. 1a and b). After 14 years of growth, the height differences were about 29%, with tree heights on the NVR treatment being significantly shorter (Table 3, Fig. 2a). Tree diameter, biomass and stem volume are shown after 14 years in Fig. 2b–d. Diameter was significantly greater for the 100S + 100H treatment. At this time, Douglas-fir with understory shrub and herb vegetation removed (100S + 100H) had stem diameters 70% larger than trees on the NVR treatments ($P = 0.001$, Table 3). Crown widths were nearly 48% greater at 15 years on 100S + 100H treatments than on NVR treatments. As hypothesized, overall survival, biomass growth, and stem volume were greater after 14 years with $\geqslant$75% shrub and herb removal.

By 5 years, Douglas-fir needle SLA differed significantly ($P < 0.04$) and was 18% higher on NVR plots than on 100S plots (82 vs. 66 $cm^2\ g^{-1}$), probably reflecting shading differences (Table 2). By 15 years stand age, there were no differences in SLA among treatments (Table 3). However, LA per tree and LAI were significantly lower for the NVR treatment at 15 years than for the 100S and 100S + 100H treatments (Table 3). The LAI for the NVR treatment was 40% and 37% of the LAI for the 100S and the 100S + 100H treatments, respectively, at 15 years (Table 3). By 15 years, PAR light levels were <1% of full sun for readings taken at 15 cm above the ground for all three treatments (data not shown). Douglas-fir LA and LAI were significantly reduced by 15 years in the presence of an understory having an estimated biomass of 15,176 (3527 SE) kg ha^{-1} on NVR treatments (Table 3).

Table 1
Percent survival of planted Douglas-fir at 15 years stand age by vegetation treatment and vegetation zone.

Vegetation removal treatment	Spruce zone (south aspect)	Spruce zone (north aspect)	Hemlock zone (south aspect)	Hemlock zone (north aspect)	Treatment mean
No removal	100.0	68.0	48.0	24.0	60.0 (16.1) a
25% shrub	96.0	64.0	44.0	56.0	65.0 (11.1) a
50% shrub	96.0	68.0	68.0	64.0	74.0 (7.4) a
75% shrub	88.0	92.0	80.0	88.0	87.0 (2.5) b
100% shrub	92.0	96.0	88.0	84.0	90.0 (2.6) b
100% shrub + 50% herb	96.0	100.0	88.0	96.0	95.0 (2.5) b
100% shrub + 100% herb	92.0	100.0	84.0	80.0	89.0 (4.4) b
Zone mean	94.3 (1.5)	84.0 (6.2)	71.4 (7.1)	70.3 (9.3)	

Note: Means with the same letter for each treatment are not significantly different at $P < 0.05$. Standard errors (SE) are shown in parentheses.

Table 2
Means and SE for aboveground biomass and related ecosystem components of trees, shrubs, and herbs in Douglas-fir plantations after five growing seasons under three levels of vegetation removal.

Vegetation	Biomass component	No removal	100% S	100% S + 100% H
Douglas-fir	Height (cm)	174.3 (28.5) a	253.4 (9.3) b	317 (13.3) c
	10 cm diameter[a] (mm)	20 (5.3) a	42.7 (4.1) b	73.6 (7.9) c
	Leaf dry weight (g)	98 (47) b	334 (57) b	945 (181) a
	Branch dry weight (g)	96 (54) b	385 (78) b	1380 (317) a
	Stem dry weight (g)	395 (193) b	1358 (235) b	3900 (756) a
	Weight per tree (kg)	0.59 (0.29) b	2.08 (0.37) b	6.19 (1.24) a
	Tree biomass (kg ha^{-1})	617 (310) b	2136 (806) b	6163 (1448) a
	Tree biomass N (kg ha^{-1})	5 (2.5) a	14 (2.0) a	44 (9.6) b
	Projected SLA[b] (cm^2 g^{-1})	81.7 (6.6) a	65.8 (1) b	69.5 (1.1) b
	Needle length (cm)	2.8 (0.1) a	2.96 (0.015) a	3.03 (0.02) a
Shrubs	Shrub biomass (kg ha^{-1})	9142 (1633)	0	0
	Shrub biomass N (kg ha^{-1})	87 (19)	0	0
Herbs	Herb biomass (kg ha^{-1})	969 (244) a	5400 (1009) b	0
	Herb biomass N (kg ha^{-1})	15 (3) a	74 (18) b	0
Shrub and herb biomass (kg ha^{-1})		10111 (1642) a	5400 (1009) b	0
Total aboveground biomass (kg ha^{-1})		10728 (1760) a	7536 (1373) b	6163 (1333) b
Total aboveground biomass N (kg ha^{-1})		107 (21) a	88 (18) ab	44 (9.6) b
Total root biomass at 0–15 cm (kg ha^{-1})		2583 (468) a	3444 (436) a	263 (77) b

Note: Means with the same letter within a row are not significantly different at $P = 0.05$.
[a] Stem diameter at 10 cm above the soil surface.
[b] SLA = specific leaf area.

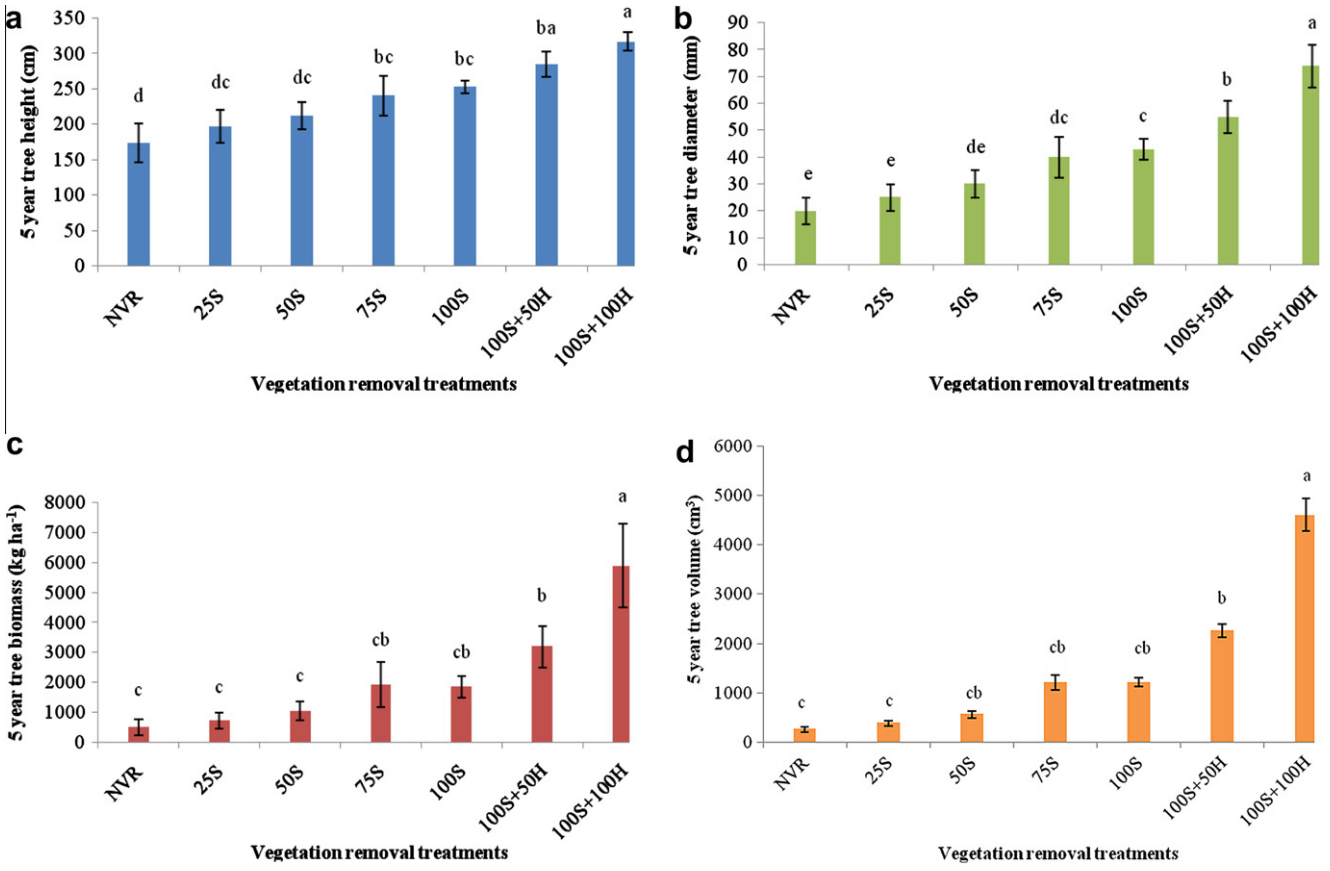

Fig. 1. Mean 5 year Douglas-fir (a) height, (b) tree diameter 10 cm above the soil surface, (c) biomass, and (d) tree volume with seven vegetation removal treatments: NVR = no vegetation removal; 25S = 25% shrub removal; 50S = 50% shrub removal; 75S = 75% shrub removal; 100S = 100% shrub removal; 100S + 50H = 100% shrub + 50% herb removal; 100S + 100H = 100% shrub + 100% herb removal. Values are means ± one standard error. Mean values represented by bars under the same letter are not significantly different at $P = 0.05$.

3.2. Biomass

After 5 years of growth, tree biomass was reduced in the presence of shrub and herbaceous vegetation ($P < 0.0001$). Douglas-fir tree biomass ha^{-1} was 10 times greater for the 100S + 100H treatment than for the NVR treatment after 5 years (Table 2, Fig. 1c). After 14 years of growth, Douglas-fir on the 100S and 100S + 100H treatments had 305% and 366% more standing tree biomass ha^{-1}, respectively, than those on NVR plots (Table 3, Fig. 2c). Tree stem volume also was substantially greater after

Table 3
Means and SE for aboveground biomass and related ecosystem components of trees, shrubs, and herbs in Douglas-fir plantations after 14 growing seasons under three levels of vegetation removal.

Vegetation	Biomass component	No removal	100%S	100%S + 100%H
Douglas-fir	Height (m)	8.2 (0.3) a	10.2 (0.3) b	10.6 (0.1) b
	DBH (cm)	10.3 (0.8) a	16.6 (0.5) b	17.5 (0.5) b
	Crown width (cm)	277 (43) a	353 (49) ab	411 (58) b
	Live crown ratio (%)	60 (3) a	65 (3) a	65 (4) a
	Leaf dry weight (kg)	3.6 (0.5) a	9 (0.7) b	10.4 (0.3) b
	Branch dry weight (kg)	7.4 (1.2) a	22 (2.1) b	26.1 (0.9) b
	Bole dry weight (kg)	16.8 (2.4) a	43 (3.5) b	49.9 (1.6) b
	Weight per tree (kg)	28 (4) a	73.6 (6) b	85.7 (2.8) b
	Tree biomass (kg ha^{-1})	17220 (5770) a	69733 (5562) b	80301 (4828) b
	Tree biomass N (kg ha^{-1})	89 (30) a	277 (28) b	298 (24) b
	Projected SLA[a] (cm^2 g^{-1})	59.5 (0.9) a	55.7 (3.6) a	59.3 (1) a
	LA per tree (m^2)	50.2 (3.1) a	81.1 (1.9) b	89.5 (5.2) b
	LAI (m^2 m^{-2})	3.1 (0.9) a	7.7 (0.3) b	8.4 (0.7) b
Shrubs	Shrub biomass (kg ha^{-1})	15020 (3556) a	3516 (1085) b	Negligible[b]
	Shrub biomass N (kg ha^{-1})	202 (49) a	36 (13) b	Negligible
Herbs	Herb biomass (kg ha^{-1})	156 (70) a	261 (132) a	Negligible
	Herb biomass N (kg ha^{-1})	3.4 (1.4) a	5 (1.5) b	Negligible
Shrub and herb biomass (kg ha^{-1})		15176 (3527) a	3777 (988) b	Negligible
Total aboveground biomass (kg ha^{-1})		32396 (4280) a	73510 (6223) b	80301 (4828) b
Total aboveground biomass N (kg ha^{-1})		294 (40) a	318 (38) a	298 (24) a
Total root biomass at 0–15 cm (kg ha^{-1})		3911 (573) a	4608 (1265) a	4517 (1044) a

Note: Means with the same letter within a row are not significantly different at $P = 0.05$.
[a] SLA = specific leaf area.
[b] A few small herbs and shrubs were scattered across these plots.

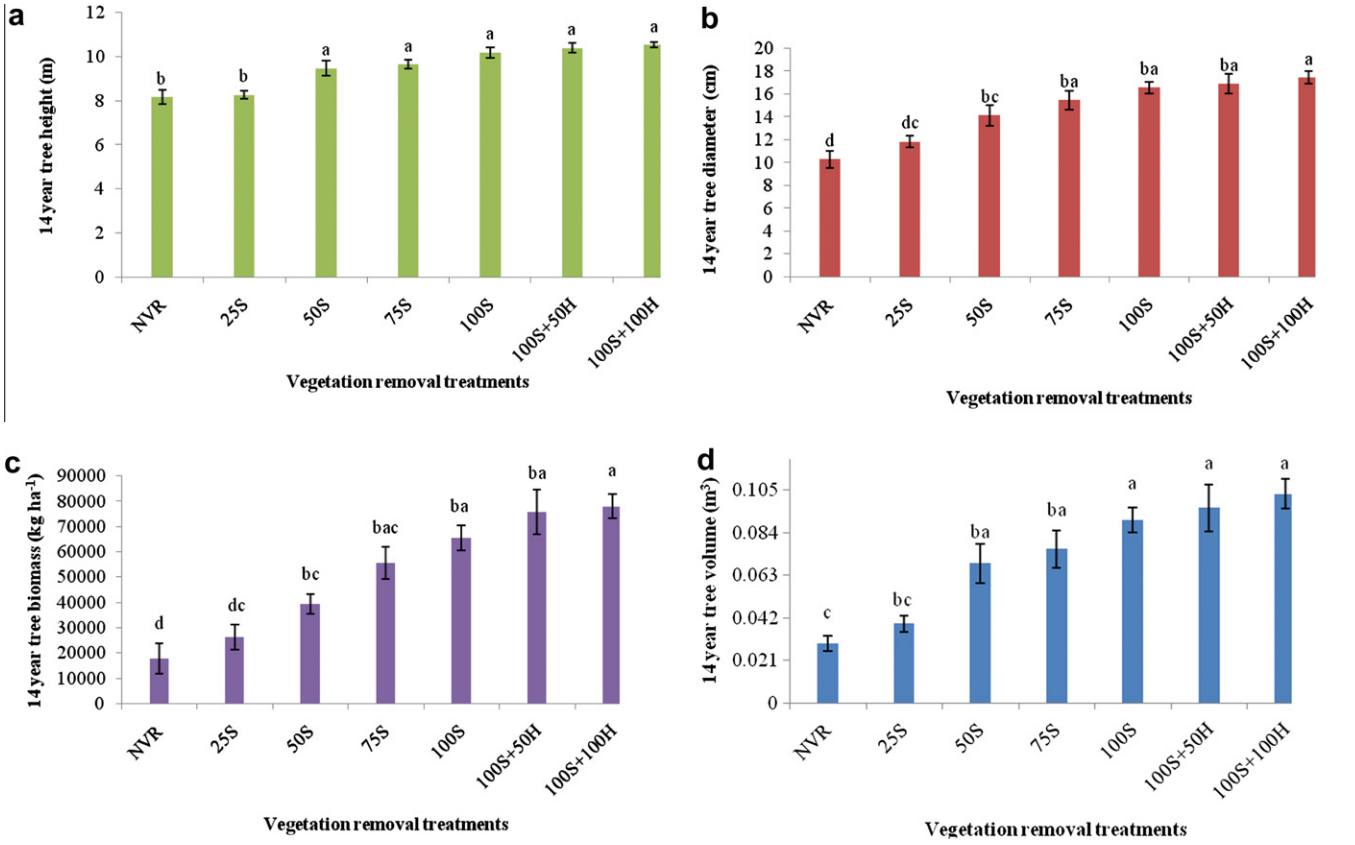

Fig. 2. Mean 14 year Douglas-fir (a) height, (b) tree diameter at DBH (137 cm) above the soil surface, (c) biomass, and (d) tree volume with seven vegetation removal treatments: NVR = no vegetation removal; 25S = 25% shrub removal; 50S = 50% shrub removal; 75S = 75% shrub removal; 100S = 100% shrub removal; 100S + 50H = 100% shrub + 50% herb removal; 100S + 100H = 100% shrub + 100% herb removal. Values are means ± one standard error. Mean values represented by bars under the same letter are not significantly different at $P = 0.05$.

14 years for the 100S + 100H treatment than for the NVR and 25S treatments (Fig. 2d). These differences in tree biomass ha^{-1} among treatments were influenced by survival differences (Table 1) and differential height and diameter growth. Total aboveground

biomass for the NVR plots was significantly lower at 15 years, and was 44% and 40.3% of the total aboveground biomass for the 100S and 100S + 100H treatments, respectively (Table 3).

The availability of environmental resources was expressed not only by increased tree growth but also by 78% more leaf area per tree after 14 years on 100S + 100H plots than on NVR plots (Table 3). The presence of understory vegetation on NVR plots significantly reduced the standing biomass of Douglas-fir at 15 years on a per tree and per hectare basis ($P < 0.0001$). An average tree on 100S + 100H plots had 3.1 times greater biomass than a tree on NVR plots at 15 years (Table 3). At or above 75% shrub removal, no additional increase in tree biomass was noted (Fig. 2c). For tree stem volume, this occurred at $\geqslant$50% shrub removal (Fig. 2d). As hypothesized, Douglas-fir growing with full competition on the NVR treatment had the lowest aboveground tree biomass and tree stem volume after 14 years.

After vegetation removal was completed in 1989, shrubs and herbs reestablished on each treatment in different amounts (Fig. 3). By 15 years, there was a substantial difference in biomass among treatments ($P < 0.0005$). Plots that received 100% shrub removal each year from 1985 through 1989 had accumulated about 25% of the understory biomass present on NVR plots by 15 years (Table 3, Fig. 3). Plots that received 50% and 25% shrub removal had regrown similar amounts of understory biomass (~16,000 kg ha^{-1}) as NVR treatment plots at year 15 (Fig. 3). The 25S treatment had the highest understory biomass (19,600 kg ha^{-1}) at 15 years (Fig. 3). More than 92% of the understory biomass on each plot was made up of shrubs (primarily salmonberry). At 5 years, even though total understory removal increased tree biomass 10 times over that of the trees on NVR plots, the presence of shrubs and herbs offset total aboveground biomass differences among treatments, resulting in a 74% greater total aboveground biomass on the NVR plots (Table 2).

By 15 years, total aboveground plant biomass was similar between 100S and 100S + 100H treatments and significantly lower on NVR plots ($P < 0.0001$) (Table 3). Total aboveground biomass was 60% lower on NVR plots compared to 100S + 100H plots. However, trees accounted for only 53% of the aboveground biomass at 15 years stand age on NVR plots (Table 3) while trees were 95% of the aboveground biomass on the 100S plots at 15 years.

Shrub biomass was 85.2% of total aboveground biomass on NVR plots at 5 years, while herbs contributed 71.6% of total aboveground biomass on 100S plots. However, at 15 years, the contribution of herb biomass to total aboveground plant biomass was <1% in all of the treatments (Table 3). On the 100S plots where herbs were 100% of the aboveground understory biomass at 5 years, they

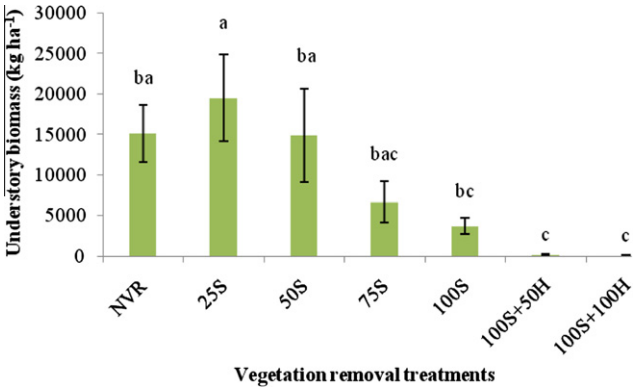

Fig. 3. Understory (shrub and herb) biomass at 15 years with seven vegetation removal treatments: NVR = no vegetation removal; 25S = 25% shrub removal; 50S = 50% shrub removal; 75S = 75% shrub removal; 100S = 100% shrub removal; 100S + 50H = 100% shrub + 50% herb removal; and 100S + 100H = 100% shrub + 100% herb removal. Values are means ± one standard error. Mean values represented by bars under the same letter are not significantly different at $P = 0.05$.

decreased to 6.9% of the understory aboveground biomass at 15 years. At 5 years, total aboveground biomass N in shrubs and herbs was 102 kg ha^{-1} on the NVR plots, while herbs alone had 74 kg ha^{-1} N on the 100S plots (Table 2). On NVR plots, shrubs and herbs had 95.3% of aboveground N at 5 years. By year 15, the NVR treatment still had 69.7% of total aboveground N in understory biomass (Table 3). As hypothesized, shrub and herb aboveground biomass N was substantially greater than Douglas-fir biomass N on NVR plots throughout this study.

Root biomass (0–15 cm) was substantially greater for both the NVR and 100S treatment plots than for the 100S + 100H plots at 5 years (Table 2). When soil cores were collected on the 100S plots having only herbs, grasses, and small Douglas-fir trees, a dense, sod-like, fine root mat was observed, while roots were quite sparse in soil core samples on the 100S + 100H plots having only Douglas-fir trees. By 15 years, root biomass was not different among treatments (Table 3).

3.3. Stable isotopes and needle N

Stable isotopes for C and N exhibited different patterns among Douglas-fir and understory vegetation components (Table 4). At plantation age 5 years, Douglas-fir needles on 100S plots had significantly more negative δ^{15}N than needles on NVR plots ($P < 0.07$). Salmonberry branches on 100S plots were more negative in δ^{13}C ($P < 0.05$) than NVR plots at plantation age 15 years. In the same 100S plots, the mean herb δ^{13}C value also was more negative than for herbs on NVR plots. Needle N concentration was significantly higher for the NVR treatment at 5 years ($P < 0.05$), but there were no significant differences in needle N concentrations among treatments at 15 years (Table 4).

3.4. Soil resources

Soil resource data for total C, total N and for soil bulk density are given in Table 5 for the 0–15 cm mineral soil depth. For 1989, there were significant differences in total soil C (<2 mm size fraction) and in total soil bulk density, with a lower %C and a higher bulk density in 1989 for the 100S + 100H treatment. By 1999, only the soil bulk density remained significantly higher in the 100S + 100H plots. There were no differences in total soil N (<2 mm size fraction) for either 1989 or 1999.

In 1989, the mean total soil C concentration was 11.4 ± 1.1% standard error (SE) and mean total N concentration was 0.63 ± 0.05% for the <2 mm size fraction of the 0–15 cm mineral soil layer, based upon initial samples collected from all four blocks. The mean soil bulk density was 0.57 ± 0.04 g cm^{-3} for the 0–15 cm mineral soil layer. No differences were observed in soil moisture concentration for the top 15 cm of the 1989 soil samples (data not shown).

In 1999, the mean total soil C concentration was 11.0 ± 0.25% and mean total N concentration was 0.60 ± 0.02% for the <2 mm size fraction of the 0–15 cm mineral soil layer, based upon initial samples collected from all four blocks. The mean soil bulk density was 0.53 ± 0.03 g cm^{-3} for the 0–15 cm mineral soil layer.

4. Discussion

4.1. Douglas-fir survival

Douglas-fir survival was not affected by the presence of understory vegetation at 5 years. Average tree survival was between 92% and 98%. Wagner (1989) reported that during the first 3 years of the experiment, a total of 4.7% of the seedlings died, with 1.7% of this mortality attributable to animal damage. He found that the

Table 4
Means and SE for $\delta^{13}C$ and $\delta^{15}N$ in Douglas-fir needles, salmonberry branches (SBB), salmonberry leaves (SBL), and herbs collected at plantation age 5 years and 15 years, together with Douglas-fir needle N concentrations.

Plantation age (years)	Vegetation component	No removal	100% shrub removal	100% shrub + 100% herb removal
5	Needle $\delta^{13}C$ (‰)	−29.1 (0.30) a	−28.6 (0.26) a	−28.7 (0.07) a
	Needle $\delta^{15}N$ (‰)	−1.5 (0.28) ab	−2.3 (0.22) b	−1.1 (0.33) a
	Needle %N[a]	1.8 (0.04) a	1.4 (0.10) b	1.6 (0.04) b
15	Needle $\delta^{13}C$ (‰)	−27.6 (0.30) a	−27.7 (0.09) a	−27.6 (0.34) a
	Needle $\delta^{15}N$ (‰)	−1.6 (0.35) a	−2.2 (0.29) a	−1.2 (0.11) a
	Needle %N[a]	1.4 (0.10) a	1.3 (0.06) a	1.4 (0.06) a
15	SBB $\delta^{13}C$ (‰)	−28.6 (0.47) a	−30.4 (0.47) b	
	SBL $\delta^{13}C$ (‰)	−29.2 (0.60) a	−30.0 (0.37) a	
	SBL $\delta^{15}N$ (‰)	−2.2 (0.42) a	−2.6 (0.32) a	
15	Herb $\delta^{13}C$ (‰)	−29.3 (0.34) a	−31.7 (0.60) b	
	Herb $\delta^{15}N$ (‰)	−2.5 (0.30) a	−1.9 (0.48) a	

Note: Means with the same letter within a row are not significantly different at $P = 0.10$.
[a] Foliar %N data were considered significant at $P = 0.05$.

Table 5
Means and SE for total soil C and N concentrations and soil bulk density from 0 to 15 cm depth on 5- and 15-year-old Douglas-fir treatment plots.

Treatments	C (%)	N (%)	Bulk density (g cm^{-3})
Five-year-old			
NVR	13.6 (1.2) a	0.72 (0.04) a	0.49 (0.035) a
100S	10.7 (0.4) ab	0.62 (0.05) a	0.59 (0.025) ab
100S + 100H	10.0 (0.9) b	0.55 (0.04) a	0.63 (0.020) b
Fifteen-year-old			
NVR	11.5 (1.3) a	0.62 (0.07) a	0.47 (0.028) a
100S	10.7 (0.6) a	0.61 (0.07) a	0.54 (0.027) ab
100S + 100H	10.8 (1.3) a	0.57 (0.08) a	0.57 (0.019) b

Note: Within a column, means with a common lowercase letter are not significantly different at $P = 0.05$.

percentage of surviving seedlings was not correlated with the abundance of woody or herbaceous vegetation during the first 3 years after planting (Wagner, 1989). On a similar site to our study area, Rose et al. (1999) did not find that competing woody and herbaceous species influenced three-year-old Douglas-fir seedling survival. Harrington (2006) found that overall conifer seedling survivorship after 5 years for western hemlock [*T. heterophylla* (Raf.) Sarg.], western redcedar (*Thuja plicata* Donn) and Douglas-fir was ⩾94%, even without competing vegetation control. By 12 years, Douglas-fir growing on the untreated vegetation treatment (control) plots had significantly lower survival than those on the seven other vegetation treatments at their Oregon Coast Range Summit research site (Rose et al., 2006). In our study, by 15 years, Douglas-fir survival declined significantly when shrub removal was less than 75% ($P = 0.034$).

Seedling growth and survival are affected by several factors. Douglas-fir seedlings are expected to grow well when they are released from overtopping weeds and planted far enough apart to avoid intraspecific competition (Rosner and Rose, 2006). Good planting stock with large seedlings also favors survival and growth (Rosner and Rose, 2006). In another study, Roth and Newton (1996) found a nearly 60% increase in Douglas-fir seedling survival (second year) with total weed control on two of three sites after planting plug-1 transplant seedlings at 0.5–1 m spacing in the Oregon Coast Range. They concluded that weed control was the dominant factor influencing seedling survival and growth. Roth and Newton (1996) also stated that weed control in conjunction with large planting stock is the silvicultural treatment that most contributes to Douglas-fir growth.

4.2. Douglas-fir growth

In our study, in Harrington (2006), and in Rose et al. (1999, 2006), similar tree spacing was used: 3 × 3 m, 3 × 3 m, and 3.05 × 3.05 m, respectively. In our study, average seedling height was 30 cm at planting time for 2–0 bare-root seedlings (Wagner, 1989). Basal area increment at 1 year after planting was not influenced by basal area at the time of planting. However, during the following 2 years, basal area and growth increment were affected by basal area and height at the start of each growing season (Wagner, 1989).

Douglas-fir seedling growth after 5 years in our study was strongly affected by the presence of understory vegetation on the blocks, with significantly greater tree height and stem diameter for the 100S and the 100S + 100H treatments than for the NVR treatment. Rose et al. (1999) found that three-year-old coastal Oregon Douglas-fir seedlings had a 70% bigger diameter (at 15 cm) and 27% greater height on herbaceous vegetation control plots than on plots with no herbaceous control. They suggested that herbs competed with seedlings for water. A similar suggestion was made by Monleon et al. (1999), who found that herbaceous vegetation had a significant effect in reducing Douglas-fir volume growth during the first 5 years. Douglas-fir volume growth loss from early herb competition continued through their entire 10 year study. While the 100S treatment significantly decreased Douglas-fir tree biomass growth during the first 5 years of our study, there was no difference in Douglas-fir biomass production between the 100S and 100S + 100H treatments after 14 years of growth (Table 3).

Rose et al. (2006) found that control of herbaceous vegetation during the first 2 years, combined with woody vegetation control for 3 years had the potential to increase Douglas-fir stem volume growth by about 355% at their Oregon Coast Range site through the 12 years of their study. Our results for 14 years of Douglas-fir growth on the 100S + 100H vegetation removal plots with a 206% increase in mean tree bole weight and a 366% increase in total tree biomass ha^{-1} (Table 3), are similar to theirs for the total vegetation control (TVC) treatment. Harrington (2006) found that complete vegetation control around seedlings of Douglas-fir and two other conifer species led to a 2.4 times increase in seedling growth (volume) during the first 4 years after a total vegetation control treatment in recent clearcuts. Our 5-year results showed a nearly 10-fold increase in stem weight and in tree biomass ha^{-1} for the 100S + 100H vegetation removal treatment relative to the NVR treatment (Table 2). In our study, however, there was no significant increase in tree biomass above 75% shrub removal after 14 years of growth (Table 3), a result consistent with data for 5-year results in other studies, where competing vegetation was kept below 25% cover during the first 5 years (Maguire et al., 2009).

A synthesis of results from 10 silvicultural studies of Douglas-fir growing with various levels of understory vegetation and/or associated woody shrubs or trees is shown in Table 6. At 5 years, our study (Table 2, Fig. 1c) and several others in Table 6 (Cole and Newton, 1987; Harrington, 2006; Petersen et al., 2008; Maguire

Table 6
Comparison of vegetation control studies and Douglas-fir volume or biomass growth response.

Study	No. of treatments	Duration (years)	Seedling type	Tree spacing (m)	Maximum growth response treatment	Alternative treatment(s)
Cole and Newton (1987)[a]	3	5	2–0 bare-root	1.23 × 1.23	Total vegetation control	Grass understory[d]
Monleon et al. (1999)	9	10	1 + 1 bare-root	3 × 3	Total vegetation control ⩽6750 ha^{-1}	Herb control & ceanothus[b] ⩽6750 ha^{-1}
Harrington (2006)	3	5	1 + 1 bare-root	3 × 3	Total vegetation control: 9 m^2 tree^{-1} on clearcuts	Vegetation control[b]: 4.5 m^2 tree^{-1}
Petersen et al. (2008)	2	5	1 + 1	2.5 × 2.5	Total vegetation control	No veg. control[d]
Maguire et al. (2009)	7	5	Styro-15	3 × 3	Total vegetation control	1st 4 years veg. control[b]
Rose and Rosner (2005)	6	8	1 + 1	3.05 × 3.05	Total vegetation control: 9.63 m^2 tree^{-1}	Vegetation control[b]: 5.95 m^2 tree^{-1}
Rose et al. (2006)	8	12	1 + 1	3.05 × 3.05	Total vegetation control: 9.63 m^2 tree^{-1}	Vegetation control[b]: 5.95 m^2 tree^{-1}
Newton and Cole (2008)	4	26	2 + 0 bare-root	2.4 × 2.4, PCT[c] to 4.5 × 4.5	Total vegetation control	Low density hardwood clumps[d]
Harrington and Tappeiner (2009)	4 or 5	23	2 + 0 bare-root	3.05 × 3.05 or 2.7 × 2.7, PCT[c] to 4.3 × 4.3	Total hardwood & understory herb control	Hardwood relative cover[b] ⩽25%
This study	7	14	2–0 bare-root	3 × 3	Total vegetation removal (100S + 100H)	Vegetation removal[b] ⩾75%

[a] For this study comparison, the maximum tree spacing is used.
[b] Alternative treatment was not significantly different from maximum growth response treatment.
[c] PCT = pre-commercial thinning.
[d] Alternative treatment had lower (21–52%, depending on the study) tree mass or volume growth.

et al., 2009) show that the maximum growth response treatment is complete vegetation control. At 5 years, two studies in Table 6 (Harrington, 2006; Maguire et al., 2009) shows that there is an alternative treatment that does not differ significantly from the complete vegetation control treatment. Research conducted for longer time periods (8, 10, 12, 14, 23, 26 years) shows either consistent trends with earlier results (Monleon et al., 1999; Rose and Rosner, 2005; Rose et al., 2006) or exhibits a significant change over time, such as the results from our study after 14 years (Tables 3 and 6, Fig. 2c). Seven of the 10 studies compared in Table 6, including ours, provide evidence for an alternative vegetation control treatment for Douglas-fir that does not differ significantly from the maximum growth response treatment. In our study, after 14 growing seasons, there were three alternative Douglas-fir treatments, 75S, 100S, and 100S + 50H (Fig. 2c), which did not differ significantly from complete vegetation control (100S + 100H). Three other studies in Table 6 (Cole and Newton, 1987; Petersen et al., 2008; Newton and Cole, 2008), had alternative vegetation control treatments that were less productive for Douglas-fir by 21–52%, depending on the study, for Douglas-fir. Retaining some competing vegetation may allow a different understory or canopy structure to persist, perhaps for differing ecosystem objectives such as wildlife habitat, possible root disease mitigation, or for increasing total ecosystem production, as suggested by Harrington and Tappeiner (2009). A white spruce study in Canada in two different boreal forest areas also found that there were one or more alternative vegetation control regimes which gave similar stem volume indexes after 5 years (Pitt et al., 2010).

Cole and Newton (1987) found that aboveground tree weight for the Douglas-fir tree only treatment after five growing seasons at the widest spacing, 1.123 × 1.123 m, was about 60% of the mean aboveground tree weight we observed in our 100S + 100H treatment after five growing seasons (Table 2). In their study, the Douglas-fir with grass treatment at the same spacing had about 20% greater tree weight than our 100S treatment having only herbaceous vegetation competition (Table 2). Mean total soil N concentration was lower (0.39% N) in the Douglas-fir only treatment site (Cole and Newton, 1986) than our mean total soil N concentration (0.63% N), which may have contributed to the ~40% lower Douglas-fir tree weight observed by Cole and Newton (1987) after 5 years of growth. In a related component of their research, Newton and Cole (1991) found that the Douglas-fir root biomass increased substantially for the Douglas-fir only planting treatment at the same 1.123 × 1.123 m planting density.

Light, soil moisture and soil nutrient availability are important factors influencing seedling growth (Roberts et al., 2005; Parker et al., 2009). In our study, light availability for Douglas-fir seedlings during the first 5 years may have been different among treatments. Wagner (1989) suggested that woody species cover was strongly correlated with available sunlight 3 years after planting, but herbaceous vegetation was not correlated with it.

Secondly, available soil water can be a limiting factor to tree seedling growth (Tappeiner et al., 2007). After the third year of this study, the cumulative soil water potential was negatively correlated with the abundance of woody neighbors (Wagner, 1989). Soil water depletion by woody and herbaceous vegetation decreased with increasing soil depth. Herbaceous vegetation decreased cumulative water potentials at 30 and 60 cm soil depths. Even though cumulative water potential decreased with increasing abundance of understory vegetation, soil water stresses were relatively low. Daily potentials rarely fell under −0.1 MPa during any of the growing seasons in the first 3 years of the plantations (Wagner, 1989). Our data (not shown) indicate that soil moisture was not significantly different among treatments, and $\delta^{13}C$ values of Douglas-fir needles also did not indicate moisture stress for any of the treatments at 5 years or by 15 years (Table 4). This is consistent with the results of Ares et al. (2008) for Douglas-fir needles.

Thirdly, soil nutrient availability can be an important site factor in tree growth (Fisher and Binkley, 2000). However, soil N concentration probably was not a limiting factor in determining seedling growth in our study, since these soils had a mean soil total N concentration of 0.63 ± 0.05% N for the 0–15 cm soil depth in the <2 mm size fraction, which was similar to the mean soil N concentration of 0.61 ± 0.04% for the 0–15 cm soil depth in a coastal Oregon young-growth Douglas-fir plantation mixed with red alder (Cromack et al., 1999). The soil N concentration also was similar to the mean soil N concentration (0.69% N) for the four highest mineral soil N concentrations observed for the 1–10 cm soil depth among 11 Douglas-fir sites located on sedimentary soils in the Oregon Coast Range (Perakis et al., 2006). Douglas-fir needle N concentrations at 5 years suggest that N was adequate for the NVR treatment, which had the highest needle N concentration (Table 4),

but was less than optimal for the other two treatments when compared with two later studies of Douglas-fir competing with understory vegetation (Roberts et al., 2005; Harrington, 2006). Reduced light levels, coupled with competition for other nutrients may have been contributing factors retarding Douglas-fir growth during the first 5 years. On the 100S plots, herbs may have competed with the Douglas-fir seedlings for nutrients and water, given the dense, sod-like herbaceous root systems that were present. On this treatment, 84% of total aboveground N content (Table 3) and 75% of total aboveground P content was in herb biomass at 5 years (Yildiz, 2000). Roberts et al. (2005) estimated that competing vegetation had 2532 kg ha^{-1} of biomass and had taken up 34.1 kg ha^{-1} of N after 3 years of Douglas-fir seedling growth with no vegetation control, indicating substantial early competition for soil N by shrubs and herbs.

The increase in soil bulk density on the 100S + 100H treatment plots (Table 5), coupled with a lower total C after 5 years may reflect the effects of vegetation removal. There were no differences in total soil N, however, and total soil C was not different after 15 years. The soil bulk density was still different at 15 years. This study afforded an opportunity to compare long-term effects on soils, as has been done in other studies of forest soil responses to long-term changes in forest species (Fisher and Binkley, 2000; Rothe et al., 2002). In agreement with McFarlane et al. (2010), net mineralizable N after 5 years was lowest on the 100S + 100H treatment (Yildiz, 2000).

4.3. Ecosystem biomass

Removing understory biomass using six different vegetation removal treatments during the 5 years following tree planting in 1985 assured successful tree establishment in those treatments, with a higher overall survival rate and biomass accumulation for Douglas-fir on the four most intensive treatments by 15 years. When understory removal treatments were stopped after the 1989 growing season, some shrubs and herbs were reestablished on plots during the following years. By 15 years, there was a significant difference in the amount of understory biomass among treatments (Fig. 3), with the largest biomass on the 25S treatment.

Salmonberry, an important understory component in our study, can achieve a high leaf area (Wagner and Radosevich, 1991; Tappeiner et al., 1991, 2001). Salmonberry is an important plant for wildlife (Hayes and Hagar, 2002). This shrub has an extensive branch network, dense foliage and an extensive rhizome and fine root system (Tappeiner et al., 1991), which may help to protect the soil from erosion, leading to greater slope stability until a closed tree canopy occurs (Keim and Skaugset, 2003; Keim et al., 2006).

In our study, 61% of the shrub biomass observed at 15 years on the NVR treatment plots was achieved during the first 5 years (Tables 2 and 3). This was likely facilitated by sprouting from established shrubs that were initially cut back to within 15 cm of the ground before seedlings were planted on the NVR treatment plots in spring, 1985 (Wagner and Radosevich, 1998). However, the salmonberry-dominated aboveground mean biomass of 15,020 kg ha^{-1} at 15 years on the NVR plots (Table 3) was about 46% of the mean of 32,250 kg ha^{-1} of salmonberry aboveground biomass observed on older clearcuts (13–18 years) by Tappeiner et al. (1991-Fig. 3). After 5 years on NVR plots, the salmonberry-dominated aboveground mean biomass of 9142 kg ha^{-1} (Table 2) was similar to the mean of 8750 kg ha^{-1} of salmonberry aboveground biomass observed by Tappeiner et al. (1991-Fig. 3) for young clearcuts. In comparison, a shrub-dominated understory at age 15 achieved 22.5% of the total live aboveground C biomass on a ponderosa pine plantation site in northern California (Zhang et al., 2008). At 15 years in our study, the shrubs that subsequently invaded the 100S removal plots comprised only 4.8% of total aboveground biomass, while comprising 46.3% of total aboveground biomass on the NVR plots. More than 92% of the understory biomass on the NVR and 100S treatment plots at 15 years was accounted for by shrubs, especially salmonberry (Table 3). Wagner and Radosevich (1998) observed that salmonberry comprised 45% of cover and thimbleberry comprised 16% of cover in 1990 on these plots.

4.4. Limitations to forest ecosystem productivity

Previous research on Douglas-fir productivity by Waring et al. (1981), summarized by Waring and Schlesinger (1985), provided evidence that maintenance of a Douglas-fir sustained high productivity rate suggests that the tree canopy LAI be kept between 4 and 6 m^2 m^{-2}. By 15 years in this study, the LAI indices were 7.7 and 8.4 m^2 m^{-2} for the 100S and the 100S + 100H treatments, respectively, while the NVR treatment LAI was only 3.1 m^2 m^{-2} (Table 3). Since interception of photosynthetically active radiation (PAR) was >99% on the NVR treatment, we estimated a total LAI of 9–10 on the NVR plots, consistent with an extinction coefficient of $k = 0.5$ for shrub and herb foliage, using the Beer-Lambert law calculation method for estimating LAI (Waring and Running, 2007). Thus, the understory vegetation would have had an LAI of at least 6.

Early seral vegetation dominated by herbs and shrubs which compete with Douglas-fir and other timber-producing species, also contributes to ecosystem productivity, nutrient cycling functions, and ecosystem biodiversity, helping to protect the soil resources and providing wildlife habitat (Waring and Running, 2007; Perry et al., 2008). In our study, and in six other studies shown in Table 6, one or more alternative treatments retain(s) a portion of the competing vegetation with herbs, shrubs, or other tree species. Even where Douglas-fir growth is significantly lower, as in three of the studies in Table 6, substantial understory functions are retained. At 15 years in our study, the 75S treatment retained 34% of the understory biomass of the 25S treatment (Fig. 3). However, understory biomass was greatly suppressed on the 100S + 50H and 100S + 100H treatments (Fig. 3). Thus, managers may have substantial flexibility for retaining a significant fraction of understory vegetation through more than 20 years for some Douglas-fir forest ecosystems, depending upon vegetation treatment regimes, initial planting density, and subsequent thinning of established stands. Inclusion of both tree and understory vegetation responses to changes in forest ecosystem productivity can be accommodated in these types of silvicultural studies, as well as providing quantitative assessments of wildlife habitat changes in understory plant species diversity and in vegetation structural heterogeneity (Wagner et al., 2004, 2006; Wilson and Puettmann, 2007; Puettmann et al., 2009; Betts et al., 2010; Ares et al., 2010; Ellis and Betts, 2011).

In our study, Douglas-fir foliage exhibited $\delta^{15}N$ values for the three treatments analyzed for both 1989 and 1999, with no significant differences evident (Table 4). The $\delta^{15}N$ values for Douglas-fir are consistent with other work on ectomycorrhizal tree species (Hobbie et al., 2009). Interestingly, our Douglas-fir foliar data show a consistently less depleted pattern for $\delta^{15}N$ than for two species of spruce in Alaska (Hobbie et al., 2009), which were growing in N-limited ecosystems.

In order to investigate water and light limitation, Douglas-fir needles, shrub branches, shrub leaves, and also herbs (sword fern) were analyzed for $\delta^{13}C$ isotopic composition. We did not detect differences among Douglas-fir needle $\delta^{13}C$ composition at 5 years or at 15 years (Table 4). Salmonberry branches at 15 years showed a 1.8‰ decrease in $\delta^{13}C$ on 100S plots compared to NVR plots ($P < 0.1$). One possible explanation for this difference in shrub $\delta^{13}C$ isotope compositions is the lower light intensity in the understory on 100S plots than on the NVR plots, due to differences in LAI (Table 3). Understory plants under greater canopy shade (100S),

with a tree canopy LAI of 7.7, may have more negative $\delta^{13}C$ values compared to NVR understory plants, with a tree canopy LAI of 3.1, that were exposed to more light at 15 years, similar to other work (Staples et al., 2001).

The herb species on every plot were shaded by trees, shrubs, or a combination of both, so that herbs on every plot may have utilized some decomposition derived CO_2 sources. If source effects were the environmental parameter responsible for these variations, then we would have expected the most negative $\delta^{13}C$ isotope ratios in the herb layer and the least negative values in trees, but no differences in the herb isotopic composition among treatment plots. The CO_2 source or shading effects on decreased $\delta^{13}C$ values (Ehleringer et al., 1986) can be distinguished by comparing the $\delta^{13}C$ isotopic composition of herbs, which averaged 2.4‰ higher (less negative) on NVR plots at 15 years (Table 4) than on 100S plots ($P < 0.1$). This implies that water limitation for herbs was primarily responsible for the observed $\delta^{13}C$ isotopic differences between the NVR and 100S treatments. Therefore, we conclude that herbs on NVR plots had more water competition than those on 100S plots at 15 years in at least the upper part of the soil profile.

Picon-Cochard et al. (2006) found that Scots pine (*Pinus sylvestris* L.) seedlings competing for soil water availability with other vegetation had increased (less negative) $\delta^{13}C$ values as did herbs on the NVR treatment plots in our study (Table 4). Since we did not detect any ^{13}C fractionation differences in Douglas-fir needles at 15 years, we assume that these trees had adequate soil moisture early in the growing season when needles are formed, or possibly accessed water from the deeper soil profile. This is in agreement with the findings of Ares et al. (2008) for Douglas-fir foliage at 5 years.

5. Conclusions

Douglas-fir survival, biomass and stem volume were significantly lower on the NVR treatment than on either four or five of the other treatments after 14 years of growth, depending upon the variable compared. Total aboveground biomass was significantly lower on the NVR treatment. Moreover, tree parameters, including DBH, tree height, LA, and LAI were significantly greater on the 100S and 100S + 100H vegetation removal treatments after 14 years of growth, while SLA was not significantly different among treatments after 14 years.

The more open canopy condition and significantly lower tree LAI of 3.1 on the NVR treatment relative to the 100S + 100H treatment, with an LAI of 8.4, may have contributed to differences in biomass and tree stem volume after 14 years. The initially more rapidly growing trees on the100S + 100H removal treatment, with an LAI of 8.4 after 14 years were approaching a limit for which substantial thinning would have been appropriate for long-term continuation of this study. With 75% shrub removal during the first 5 years, any increase in degree of understory removal did not contribute significantly to additional Douglas-fir survival or to biomass and stem volume growth.

Presence of residual shrubs and herbs in most of the removal treatments through 14 years shows that forest ecosystem production can be increased while partially retaining some understory vegetation for wildlife habitat and maintaining soil resources during early succession, thus fostering establishment of productive, young-growth Douglas-fir stands. Given these results, forest ecosystem managers may have substantial flexibility in using early vegetation management treatments to increase long-term tree growth. Future work could evaluate the effects of planting vigorous, high-quality tree seedlings, while using selective early vegetation management regimes and suitable thinning regimes during stand development, thus improving ecosystem management along with increasing wood production.

Acknowledgements

Support for the senior author was received from Düzce University, Turkey. Research support came from the Oregon State University Forest Science Department, the US Forest Service Pacific Northwest Research Station, and the US Environmental Protection Agency. We gratefully acknowledge the assistance of Robert G. Wagner, who began the original study and shared key data for tree survival and growth from year 5. The following individuals gave helpful advice on research methods and data analysis: Carol Glassman, Jillian Gregg, Erik Hobbie, Marc Kramer, Dave Myrold, Nan Posavatz, and Chris Swanston. Dan Binkley, Elizabeth C. Cole, Douglas A. Maguire, Vicente J. Monleon, John C. Tappeiner, II, and Richard H. Waring provided helpful manuscript suggestions. Angeline S. Cromack and Kevin T. Cromack edited and formatted the final draft of the paper.

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