Synergistic stem volume response to combinations of vegetation control and seedling size in conifer plantations in Oregon

Lee S. Rosner and Robin Rose

Abstract: There are few published studies examining the effects of the interaction of seedling size and vegetation control on the growth of Pacific Northwest conifer species. Data from two vegetation management studies encompassing five planting sites, four conifer species, and two stock types were analyzed to determine the relative effects of seedling size at planting and intensity of vegetation control on subsequent seedling growth. Study 1 tested eight combinations of annual broadcast weed control or no weed control applied over the course of 5 years. Study 2 tested spot herbicide applications of differing area, as well as herbaceous-only and woody-only control treatments. The effect of seedling size was determined by analysis of covariance, with basal diameter as the covariate. Both seedling size and weed control increased growth of all conifer species through 4, 5, or 12 years, but responses varied by species and site. Diameter and height responses to weed control and seedling size were additive, whereas volume differences between treatments increased with increasing seedling size. The implication for management is that the volume return from increased weed control is maximized by planting the largest possible seedlings; conversely, the volume from increased seedling size is maximized at the highest weed control intensities.

Résumé : Peu d'études publiées se sont penchées sur l'interaction entre la taille des semis et les traitements de contrôle de la végétation dans le cas d'espèces résineuses de la région du nord-ouest du Pacifique. Les effets relatifs de la taille des semis au moment de la plantation et de l'intensité du contrôle de la végétation sur la croissance subséquente des semis ont été analysés à partir des données de deux études de maîtrise de la végétation comprenant cinq stations, quatre espèces de conifères et deux types de plants. La première étude a testé huit combinaisons de contrôle annuel en pleine surface de la végétation ou d'absence de contrôle au cours d'une période de 5 ans. La deuxième étude a testé l'application localisée d'herbicides sur différentes superficies ainsi que des traitements de contrôle spécifiques aux espèces herbacées ou aux espèces ligneuses. L'effet de la taille des semis a été déterminé à l'aide d'une analyse de covariance utilisant le diamètre au collet comme covariable. La taille des semis et le contrôle de la végétation ont augmenté la croissance de toutes les espèces de conifères après 4, 5 ou 12 ans, mais les réactions ont varié selon l'espèce et la station. Alors que les réactions en diamètre et en hauteur en fonction du contrôle de la végétation et de la taille des semis étaient additives, les différences de volume entre les traitements ont augmenté avec une hausse de la taille des semis. Pour l'aménagement, ceci implique que la réaction en volume à la suite d'une augmentation du contrôle de la végétation est maximisée en plantant les plus gros semis possibles et, réciproquement, le volume obtenu par une augmentation de la taille des semis est maximisé lorsque le contrôle de la végétation atteint les plus fortes intensités.

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Introduction

Planting a larger seedling has been shown to increase survival, height, and (or) volume production in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (van den Driessche 1992; Long and Carrier 1993; Ritchie et al. 1993; Rose and Ketchum 2003), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Newton at al. 1993), and numerous other conifer species (South et al. 1993*b*, 2001*a*; Mason et al. 1996; South and Mitchell 1999; Mason 2001; Jobidon et al. 2004). Weed control treatments applied prior to planting (site preparation) or for the first few years after planting (release) have been shown to improve growth in Pacific Northwest conifer plantations across numerous species (Newton and Preest 1988; Harrington et al. 1995; Oester et al. 1995; Stein 1995; Rose et al. 1999; Rose and Ketchum 2003).

Although it has long been recognized that both seedling size and site preparation treatments (mechanical or chemical) are important factors in the survival and growth of seedlings planted in forest plantations, the effects of both factors have most often been studied separately. South et al. (2001*b*) found that only 4 of 185 published nursery or site preparation studies examined the interaction between nursery treatments and site preparation treatments. There are several pitfalls to studying these factors separately. First, effects may be additive in some cases; they may also be redundant, synergistic, or even antagonistic. Second, even when effects are additive, there is no way to compare the magnitude of re-

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sponse to different factors unless the factors are studied under the same conditions. Since productivity goals can be achieved by various combinations of seedling stock size and vegetation management treatments (Örlander et al. 1990; South et al. 1993*b*), the only way to determine the optimal combination of these treatments, from an economic standpoint, is to study them together.

One approach to studying the effect of a seedling morphological parameter, such as initial diameter, on subsequent performance would be to incorporate seedling size into the study design as a treatment factor replicated at the plot level (or subplot level in a split-plot design). In a few cases, initial seedling size has been studied as a factor in combination with vegetation management treatments. Different approaches involve culturing groups of bare-root seedlings differently to create morphologically different classes (South et al. 2001*a*), growing seedlings in different sized containers (Jobidon et al. 2004), or dividing seedlings from the same lot into classes based on differences that arose during production (South et al. 1993*b*; South and Mitchell 1999; Rose and Ketchum 2003).

In studies looking at effects of site preparation or herbicide treatments, there are often too many treatments of interest to look at initial seedling size in factorial combination with all the other treatments, so this type of study is rarely undertaken. When initial seedling parameters are measured in these studies, the effect of seedling size can often be assessed retrospectively. At least two analytical approaches can be taken. The first involves grouping seedlings into discrete size classes (grades) post hoc and then treating seedling size as a split-plot factor. Because these size classes are created post hoc, the number of seedlings falling into each class (subplot) within a plot will vary, potentially widely, and thus the sample size for any given subplot can be extremely small. Since the whole plot size (number of planted seedlings) was originally designed to be adequate in the absence of a split-plot factor, the subplot size is potentially less than adequate, which argues for restraint in breaking up seedling sizes into too many classes. South et al. (1995) used this type of analysis with two size classes in examining the combined effects of mechanical site preparation, herbaceous weed control, fertilization, and seedling grade in loblolly pine (*Pinus taeda* L.). Mason et al. (1996) used a similar approach with three or four size classes per site in studying the combined effects of seedling size, weed control, and soil cultivation in Monterey pine (*Pinus radiata* D. Don).

The second method of retrospective analysis is analysis of covariance (ANCOVA), which is used when a variable other than the treatment of interest may be correlated with the response variable. The experimental unit for the effect of seedling size in an ANCOVA would be the individual tree (the subsampling unit), rather than the treated plot. ANCOVA creates a model that adjusts the response variable for differences in the potentially confounding variable (the covariate). Before treatment means are compared, ANCOVA requires testing for a common slope among the regression equations generated for each treatment response across the various levels of the covariate. If no treatment × covariate interaction exists, the interaction term is dropped, yielding a common-slope model. This model can then be used to test for significant treatment and covariate effects, to generate common-slope regression equations for each treatment, and to estimate treatment means at any given level of the covariate.

We have not found any example of this approach to ANCOVA being used to retrospectively examine the role of initial seedling size in studies involving silvicultural treatments applied in the field. ANCOVA can be advantageous because it allows estimation of increases in stem volume per unit increase in seedling diameter and can account for an uneven distribution of seedling sizes across treatments. In vegetation management studies, ANCOVA is frequently used to adjust responses for differences in the initial size of seedlings, with the effect of the covariate not reported (Oppenheimer et al. 1989; Perry et al. 1993; Biring et al. 2003). Puértolas et al. (2003) used ANCOVA to evaluate the effects of seedling size and nursery fertilization on growth of outplanted Aleppo pine (*Pinus halepensis* Mill.) seedlings. Our objective, therefore, is to use ANCOVA to quantify the effect of initial seedling diameter on subsequent growth across a range of vegetation management treatments and to compare the effect of seedling size relative to gains obtained through weed control for several conifer species. We hypothesized not only that growth would increase with increasing seedling diameter but also that the potential for weed control to increase growth would be the greatest in the largest seedlings planted.

Materials and methods

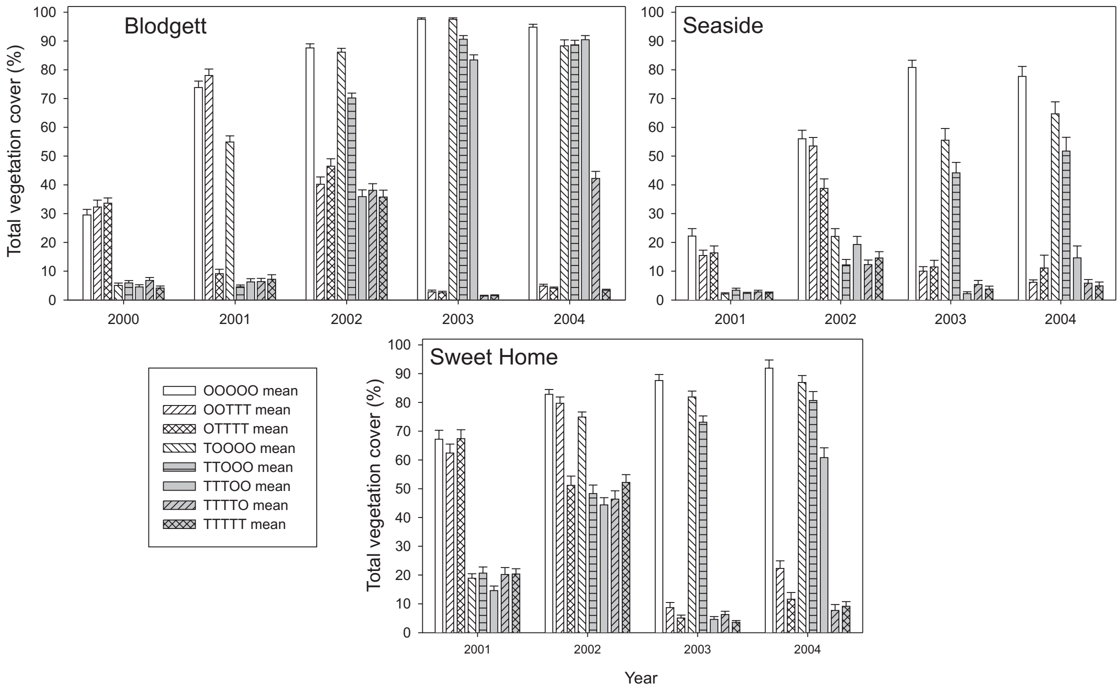
Study 1

The data sets used in this analysis come from two studies. Study 1 was established in 2000–2001. The objectives of this study were (1) to estimate the duration of continuous weed control needed to maximize early plantation growth and (2) to quantify growth losses resulting from delaying vegetation control for a year or two after planting. The study has been followed across three sites in Oregon. The Blodgett site was installed in January 2000. This site is located near the town of Blodgett, Oregon, in the central Coast Range at an approximate elevation of 250 m above sea level (a.s.l.). It receives approximately 150–280 cm of precipitation annually. The vegetation that invades after disturbance in this zone is typically composed of sword fern (*Polystichum munitum* (Kaulf.) K. Presl), salal (*Gaultheria shallon* Pursh), Oregon grape (*Mahonia nervosa* (Pursh) Nutt.), blackberry species (*Rubus* L.), and robust herbaceous communities. The site was logged the spring before planting (1999).

The Sweet Home site was installed the winter of 2001 on the western slope of the Cascade Range near the town of Sweet Home, Oregon, at elevations ranging from 182 to 244 m a.s.l. Average annual precipitation at this site is approximately 125 cm. The vegetation community in this zone is similar to that found at Blodgett and reinvades rapidly after disturbance. The site was harvested by feller–buncher in March of the year prior to planting (2000).

The Seaside site was installed the winter of 2001 near the town of Seaside, Oregon, at elevations ranging from 171 to 213 m a.s.l. in an area characterized by dense spruce–hemlock forests. These forests typically have dense overstories, and competing vegetation is slow to invade after harvest. The plant community that eventually invades is dominated by salmonberry (*Rubus spectabilis* Pursh), red

Fig. 1. Annual estimated mean total vegetative cover by treatment averaged across conifer species at the three study 1 sites.



alder (*Alnus rubra* Bong.), elderberry species (*Sambucus* L.), sword fern, and numerous herbaceous species. Mean annual precipitation is 180–250 cm.

All study installations are randomized block designs, with eight treatments replicated across three or four blocks. Treatment plots were planted with 36 seedlings in a 3.1 m × 3.1 m (10 ft × 10 ft) grid surrounded by a row of buffer trees. The eight treatments included a no treatment "check"; 1–5 consecutive years of herbicide treatments beginning the first year; 4 consecutive years of herbicide treatments beginning the second year; and 3 consecutive years of herbicide treatments beginning the third year. With "T" (herbicide treated) and "O" (untreated) representing individual years of the study, the treatments are: OOOOO, OOTTT, OTTTT, TOOOO, TTOOO, TTTOO, TTTTO, and TTTTT. Four conifer species — Douglas-fir, western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock, and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) — were tested independently at the Blodgett site, whereas Douglas-fir and western redcedar were planted at Sweet Home, and Douglas-fir and western hemlock were planted at Seaside. All seedlings were grown in 250 mL (15 in.^{3}) Styroblock containers (Beaver Plastics, Edmonton, Alta., Canada), with slow-release fertilizer in the media.

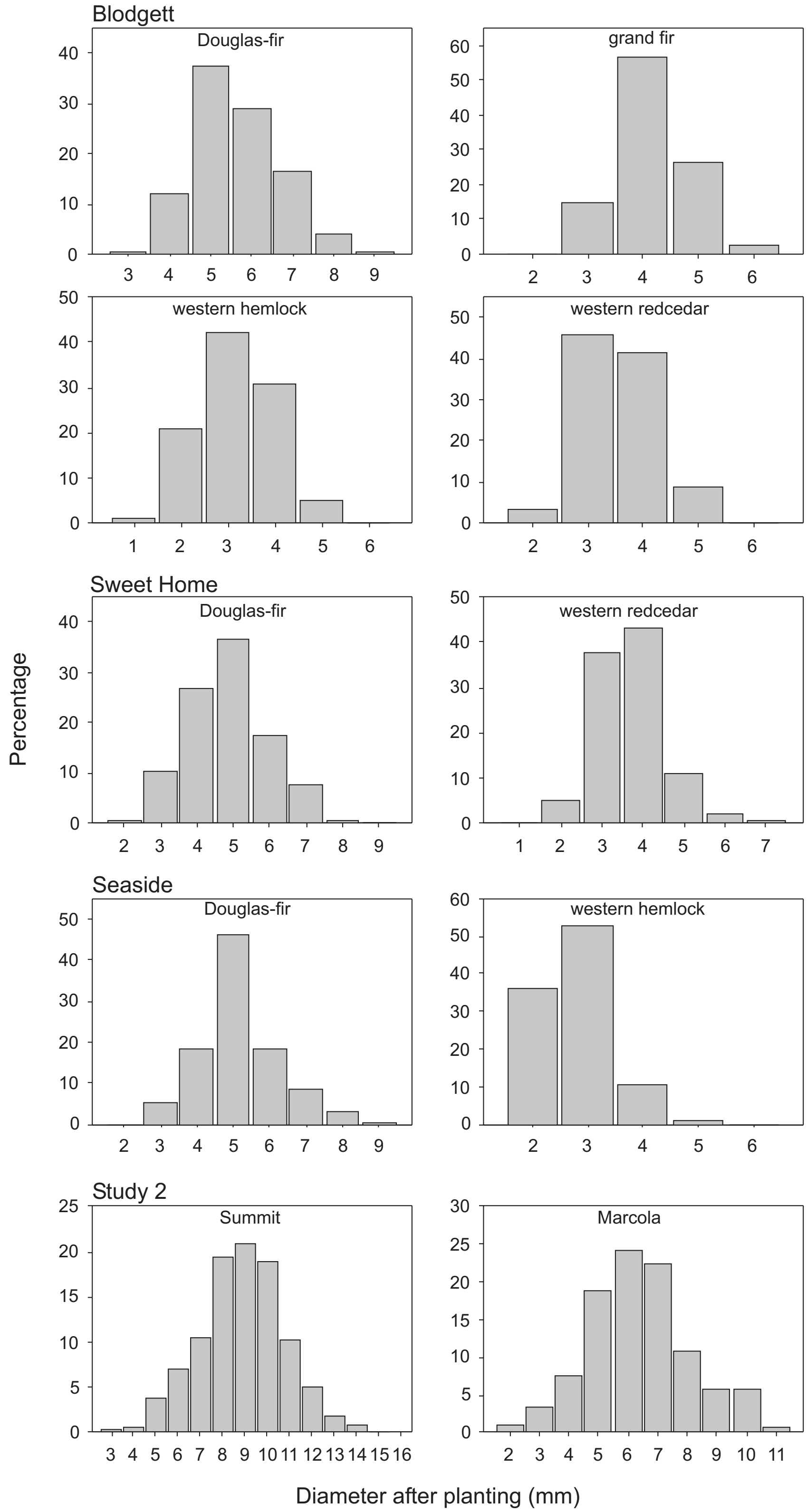
All sites received similar site preparation treatments, including excavator piling of slash outside treatment areas. While piling slash, the excavator also pulled existing shrub clumps. Because of concerns about compaction during harvest, the Blodgett and Sweet Home sites were subsoiled after completion of excavator piling. Following removal of slash, a follow-up directed herbicide treatment (imazapyr, 2.5%) was applied in all plots, including the check treatment, to control sprouting hardwoods, primarily bigleaf maple (*Acer macrophyllum* Pursh).

As part of the site preparation for all plots designated for herbicide treatment in the first year, a mixture containing sulfometuron (0.15 L/ha (2.0 ounces/acre)), metsulfuron (0.04 L/ha (0.5 ounces/acre)), and glyphosate (4.68 L/ha (64 ounces/acre)) was broadcast in the fall. Thereafter, herbicide treatments with atrazine (4.5–4.9 kg/ha (4.0–4.4 pounds/acre)) and clopyralid (0.58–0.73 L/ha (8–10 ounces/acre)) were applied each spring. Follow-up treatments with glyphosate (1.5%–2.0%) were applied in late spring or early summer. Occasionally, treatments were applied in the fall on plots designated for treatment the following year if those plots contained high levels of cover of species unlikely to be controlled by spring applications. For those applications glyphosate (1.5%–2.0%) and occasionally clopyralid (0.5%) or atrazine (4.5 kg/ha (4.0 pounds/acre)) were used. Vegetation assessments were made each July at all sites. Six permanent 1 m radius vegetation assessment subplots, each centered on a conifer seedling, were established within each plot. Cover of each vascular plant species and total vegetation cover were estimated within each subplot. Treatments reduced total vegetation cover, but the effectiveness of treatments varied across years (Fig. 1).

Initial diameter and height of all seedlings were measured in the field 1 month after planting. The overall distribution of diameters by site and species is shown in Fig. 2. Seedlings were measured annually for diameter, height, and survival every October for 4 years (Sweet Home, Seaside) or for 5 years (Blodgett). Only the final year's measurements and the initial measurements were used in this analysis. Since fourth-year data are presented for Sweet Home and Seaside, TTTTO and TTTTT treatments are essentially replications of the same treatment (TTTT) at this stage in the study. Conical volume was calculated from the following equation:

$$[1] \qquad \text{Volume} = \frac{\pi}{12} \times (\text{diameter})^2 \times \text{height}$$

Fig. 2. Histograms for initial diameter distribution by site and species in studies 1 and 2. Although some bars are not visible because of low percentages, *x*-axis labels are present only where at least one seedling was observed.

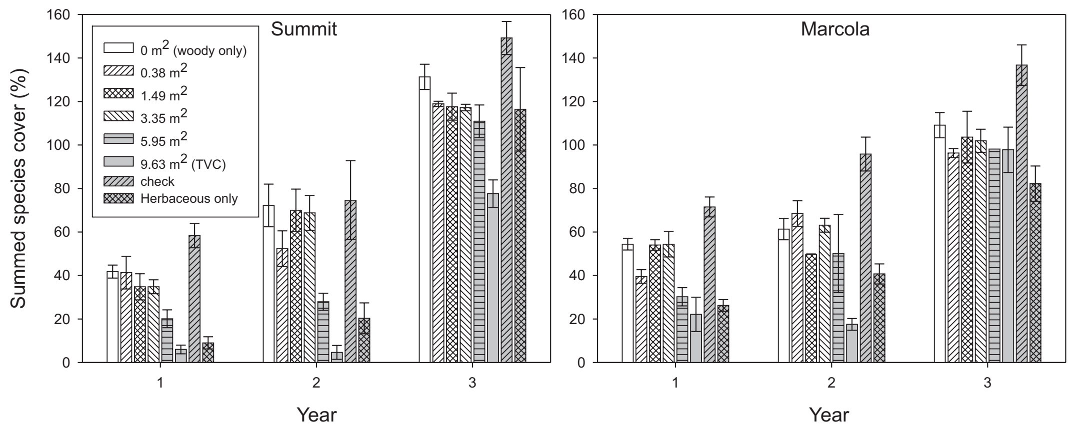


To the extent that treatments alter stem taper, both conical volume and second-growth volume equations (Bruce and DeMars 1974) may distort treatment differences.

Study 2

The second study tested Douglas-fir response to a variety of weed control treatments at three western Oregon sites,

Fig. 3. Annual estimated mean total vegetative cover by treatment averaged across conifer species for the initial 3 years at both study 2 sites.



two of which were followed for longer than 3 years and are included in this analysis: Summit, in the central Coast Range; and Marcola, on the western slope of the Cascade Range. The Summit site is located 32 km west of Corvallis, Oregon, at an approximate elevation of 234 m a.s.l. The site has slopes ranging from 2% to 20%, with aspects depending on plot location. The soil, in the Apt series, is deep and well drained, and the site index is 41 m at a base age of 50 years (King 1966). Rainfall averages 173 cm/year. This site was dominated by bigleaf maple, red alder, and bitter cherry (*Prunus emarginata* (Dougl. ex Hook.) D. Dietr.) prior to harvest. After harvest in the summer of 1992, slash was removed, the ground was scarified with ripper blades, and the site was subsoiled with a winged blade to a depth of approximately 60 cm.

The Marcola site is located east of Springfield, Oregon, on a south-southeast slope (<10%) with elevations ranging from 244 to 274 m a.s.l. Soils are of the Nekia series and are well drained and moderately deep. The site index at Marcola is 37 m at a base age of 50 years (King 1966). Rainfall averages 133 cm/year. The former stand, which consisted of 65-year-old Douglas-fir, was logged by processor and shovel in 1992. The site was then scarified and ripped in September 1992. The perimeters of both sites were fenced to prevent deer browse.

At both sites a completely randomized design with eight independent experiment treatments and three replicate plots was used. The treatments consisted of four spot herbicide applications of different areas (0.375, 1.49, 3.35, and 5.95 m^2), an untreated check, a total vegetation control (TVC) treatment equivalent to a 9.63 m^2 area of control, and treatments in which either only the herbaceous plant component or only the woody plant component was controlled. For all spot treatments, herbaceous treatments were applied within the spots, and all woody competition was controlled in the entire plot. Thus, only herbaceous competitors were present outside the treated areas. Herbaceous vegetation control treatments were maintained for the first 2 years after planting, and woody vegetation control treatments were maintained for 3 years. At both sites 2-year-old bare-root Douglas-fir seedlings were planted. The 1 – 1 seedlings were grown the first year in a seedling bed and the second year in a transplant bed. Rose et al. (1999) provided a detailed description of the study methodology.

Competing cover was assessed each of the first 3 years after planting within four 6 m × 6 m subplots per plot. At both sites increased area of vegetation control tended to decrease total vegetation cover, although treatments at Summit tended to be more effective in reducing cover through year 2 than at Marcola (Fig. 3). Grass species, the dominant herbaceous species at Summit, were well controlled by weed-control treatments, but bracken fern (*Pteridium aquilinum* (L.) Kuhn), the dominant species at Marcola, was difficult to control (Rose et al. 1999). Beginning about year 5 at Summit, bitter cherry began to dominate plots in which woody species were not controlled, reducing Douglas-fir growth and increasing mortality (Rose and Rosner 2005). Competitive woody species were not present in significant numbers at Marcola.

Basal diameter and height were measured shortly after planting. The overall distribution of diameters by site is shown in Fig. 1. Twelfth-year diameter at breast height (DBH), height, and survival data, as well as measurements taken immediately after planting, are used in these analyses. Twelfth-year stem volumes for individual trees were calculated with volume equations derived for second-growth Douglas-fir (Bruce and DeMars 1974).

Analysis

ANCOVA was run separately on the most recent measurements of diameter, height, and stem volume for each site–species data set using PROC MIXED version 8.2 software (SAS Institute Inc. 1989). Initial diameter measured shortly after planting was used as the covariate. Treatment means were compared by using Fisher's protected LSD test and a significance level of $\alpha = 0.05$. Prior to analysis, assumptions of homogeneity of variances and normality were tested for each independent analysis. Diameter and height data were normally distributed with equal variances in every case, except western redcedar at Sweet Home. In that instance, a natural-log transformation of both parameters was needed to satisfy assumptions. In every case, variances for volume were highly heterogeneous, with greater variance occurring with greater expected values. With the exception of western redcedar at Sweet Home, the natural-log transformation of volume data was too extreme, and variances tended to decrease with increasing expected value. A cube-root transformation proved to be best at correcting heterogeneity of variances and maintaining normality. Therefore, volume data were cube-root transformed, except for western redcedar at Sweet Home, which required a natural-log transformation.

Our initial step in ANCOVA involved checking for interactions between treatment factors (site, species, and treatment) and the covariate: where factors interact with the covariate, a common-slope ANCOVA cannot be run. In study 1 we analyzed sites and species within site separately. Sites were analyzed separately because the Blodgett site was initiated 1 year earlier than the other two sites, and different sets of species were tested at different sites. At Sweet Home the data for each species required different transformations to conform to model assumptions, so each species was analyzed separately. At the Blodgett and Seaside sites, where each growth parameter required the same transformation for all species, we initially included both the treatment and the species factors in the model when testing for significant interactions with initial diameter. At Blodgett there were highly significant ($p < 0.0001$) interactions between initial diameter and species for volume, diameter, and height. Therefore, to run a common-slope ANCOVA for the response to treatments across differing levels of the covariate, we analyzed each species separately. At Seaside initial diameter did not interact with volume ($p = 0.19$), diameter ($p = 0.57$), or height ($p = 0.38$), but for consistency in analysis, we dropped the species factor for the ANCOVA and ran species data separately, noting that the response to initial diameter was not significantly different between species. When we included site in the test of model assumptions in study 2 (only one species, Douglas-fir, was tested), there were significant site × covariate interactions for volume ($p = 0.01$) and DBH ($p = 0.01$) but not for height ($p = 0.05$), although when the height response to initial diameter was plotted by site, the slope was greater for the Summit site. To use a common-slope model across all three parameters required running each site separately.

There were no significant interactions between initial diameter and treatment for any of the 12th-year parameters evaluated in study 2 (Table 1). In study 1, there were only two significant treatment by initial diameter interactions across all sites, species, or parameters (p =.046 in both cases): one at Blodgett and one at Sweet Home. In both cases, when the interaction term was plotted, the difference in slopes neither appeared biologically significant nor conformed to any pattern related to treatment intensity. Therefore, the common-slope ANCOVA model was run for all parameters in all species at all sites.

Results

Study 1

Blodgett

Both weed control treatments and initial diameter significantly affected fifth-year diameter, height, and volume in all four species (Table 1). Volume growth through 5 years tended to be greater with increasing years of weed control for all species, although 1 year of weed control (TOOOO) elicited little response relative to the check (OOOOO), and 3 years of initial weed control (TTTOO) had little effect relative to 2 years of initial weed control (TTOOO) (Table 2). Fifth-year diameter and height increased with increasing initial diameter for all species, but the magnitude of response varied (Table 3). Western hemlock and western redcedar showed a stronger response to increasing initial seedling diameter for both diameter and height than Douglas-fir or grand fir, as reflected by higher common slope values (Table 3). For example, western redcedar fifth-year diameter increased 0.75 cm for each 1 mm increase in initial diameter — more than double the rate of increase for Douglas-fir (0.34 cm).

As a result of the greater slopes for diameter and height, estimated volume in western hemlock and western redcedar showed a greater divergence among treatments with increasing initial diameter than was observed for Douglas-fir or grand fir (Fig. 4). Planting the largest initial seedling diameter instead of the smallest increased the volume response to weed control (OOOOO vs. TTTTT) by 64% in Douglas-fir, 73% in grand fir, 172% in western hemlock, and 201% in western redcedar (Fig. 4). For the treatment closest to what is the operational norm in the Pacific Northwest (TTOOO), planting the largest initial diameter rather than the smallest increased fifth-year volume by 128% in Douglas-fir, 130% in grand fir, 423% in western hemlock, and 403% in western redcedar (Fig. 4).

Sweet Home

Weed control treatments significantly affected fourth-year diameter, height, and volume in both Douglas-fir and western redcedar (see Table 1). Initial diameter, on the other hand, affected all three parameters in western redcedar but had no effect on any parameter in Douglas-fir. Although both species responded favorably to weed control treatments, the extent of improvement varied greatly by species and parameter (see Table 2). Most noteworthy is the almost complete lack of growth (fourth-year volume <0.1 dm^3) in western redcedar when weed control was delayed for 2 years (OOTTT) or withheld entirely (OOOOO). This response reflects rapid establishment of weed cover in the first year of the study (see Fig. 1).

Common slope values for the linear response of log-transformed diameter and height indicate a robust response to initial seedling size in western redcedar (Table 3), despite no response in Douglas-fir. Planting the largest initial seedling diameter (7 mm) rather than the smallest (2 mm) increased western redcedar volume response to weed control (OOOOO vs. TTTTT) by 319% (Fig. 5). With 2 years of broadcast weed control (TTOOO), fourth-year volume in the largest diameter class of western redcedar planted was 319% greater than in the smallest (Fig. 5).

Seaside

Both weed control treatment and initial diameter significantly affected fourth-year diameter and volume for Douglas-fir and western hemlock (see Table 1). However, while initial diameter affected fourth-year height for both species, herbicide treatment had no effect on height of either species. Increasing years of weed control tended to increase

Table 1. Analysis of covariance table by site and species for volume, diameter, and height responses, with the interaction term included (to test whether the common slopes model is appropriate) and dropped for the common-slope model.

				Volume†				Diameter‡				Height§			
				Full model		Common-slope model		Full model		Common-slope model		Full model		Common-slope model	
Site	Effect*	Numerator df	Denominator df	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Study 1															
Blodgett															
Douglas-fir	Trt	7	21	3.6	0.0102	24.8	<0.0001	3.8	0.0083	30.3	<0.0001	2.5	0.0464	8.6	<0.0001
	Dia0[4]	1	1071	57.7	<0.0001	60.6	<0.0001	56.2	<0.0001	58.3	<0.0001	31.5	<0.0001	34.4	<0.0001
	Dia0 × trt	7	1071	0.5	0.8720			0.2	0.9743			1.3	0.2302		
Grand fir	Trt	7	14	2.1	0.1186	31.8	<0.0001	1.8	0.163	28.7	<0.0001	2.1	0.1194	21.7	<0.0001
	Dia0	1	774	29.1	<0.0001	27.4	<0.0001	34.2	<0.0001	32.6	<0.0001	10.9	0.001	9.9	0.0017
	Dia0 × trt	7	774	1.6	0.1198			1.7	0.1187			1.5	0.1488		
Western hemlock	Trt	7	21	4.2	0.0051	18.1	<0.0001	3.7	0.009	21.3	<0.0001	3.9	0.0072	9.6	<0.0001
	Dia0	1	986	84.3	<0.0001	86.7	<0.0001	78.4	<0.0001	80.3	<0.0001	73.8	<0.0001	76.3	<0.0001
	Dia0 × trt	7	986	1.6	0.1410			1.3	0.2684			2.1	0.0456		
Western redcedar	Trt	7	14	2.3	0.0857	4.0	0.0126	1.9	0.1482	4.3	0.0102	2.5	0.0655	3.5	0.0232
	Dia0	1	731	70.1	<0.0001	69.9	<0.0001	71.5	<0.0001	71.5	<0.0001	44.2	<0.0001	44.4	<0.0001
	Dia0 × trt	7	731	1.4	0.1880			1.5	0.1765			1.1	0.3511		
Seaside															
Douglas-fir	Trt	7	21	3.2	0.0179	7.8	0.0001	3.6	0.0105	13.6	<0.0001	1.4	0.2761	1.6	0.2039
	Dia0	1	1075	91.2	<0.0001	91.9	<0.0001	79.7	<0.0001	79.7	<0.0001	67.8	<0.0001	69.4	<0.0001
	Dia0 × trt	7	1075	1.5	0.1710			1.1	0.3754			1.2	0.2884		
Western hemlock	Trt	7	21	1.0	0.4467	3.2	0.0192	1.5	0.2351	3.3	0.0161	0.8	0.6065	1.8	0.1323
	Dia0	1	867	48.0	<0.0001	49.1	<0.0001	34.9	<0.0001	35.7	<0.0001	33.1	<0.0001	34.4	<0.0001
	Dia0 × trt	7	867	1.3	0.2638			1.3	0.261			1.2	0.3286		
Sweet Home															
Douglas-fir	Trt	7	20	5.0	0.0020	41.7	<0.0001	6.0	0.0007	50.7	<0.0001	2.4	0.0605	21.6	<0.0001
	Dia0	1	994	0.2	0.6726	0.1	0.7264	0.1	0.7284	0.1	0.7531	0.4	0.5490	0.3	0.6133
	Dia0 × trt	7	994	0.2	0.9877			0.2	0.9740			0.3	0.9705		
Western redcedar	Trt	7	21	2.2	0.0725	6.8	0.0003	2.7	0.0346	8.2	<0.0001	1.1	0.4244	4.6	0.0028
	Dia0	1	726	12.7	0.0004	10.6	0.0012	11.7	0.0007	9.0	0.0028	12.5	0.0004	13.5	0.0003
	Dia0 × trt	7	726	1.8	0.0937			2.1	0.0455			0.9	0.5450		
Study 2															
Summit															
Douglas-fir	Trt	7	16	4.9	0.0042	9.5	0.0001	4.6	0.0053	12.8	<0.0001	3.8	0.0134	3.9	0.0119
	Dia0	1	997	71.0	<0.0001	71.6	<0.0001	71.5	<0.0001	72.2	<0.0001	48.7	<0.0001	49.2	<0.0001
	Dia0 × trt	7	997	1.1	0.3753			0.9	0.5177			1.2	0.3061		

Table 1 (*concluded*).

Site	Effect*	Numerator df	Denominator df	Volume† Full model *F*	*p*	Volume† Common-slope model *F*	*p*	Diameter‡ Full model *F*	*p*	Diameter‡ Common-slope model *F*	*p*	Height§ Full model *F*	*p*	Height§ Common-slope model *F*	*p*
Marcola															
Douglas-fir	Trt	7	16	2.4	0.0722	6.6	0.0009	1.9	0.1368	6.6	0.0009	2.9	0.0378	6.1	0.0014
	Dia0	1	1067	56.8	<0.0001	58.7	<0.0001	54.7	<0.0001	56.3	<0.0001	44.2	<0.0001	46.1	<0.0001
	Dia0 × trt	7	1067	0.2	0.9926			0.2	0.9882			0.5	0.834		

*Dia0, initial basal diameter measured in the field after planting.
†Volume data were cube-root transformed in every case except for western redcedar at Sweet Home, in which data were natural-log transformed.
‡Diameter data for western redcedar at Sweet Home were natural-log transformed.
§Height data for western redcedar at Sweet Home were natural-log transformed.

fourth-year diameter and volume response in Douglas-fir (see Table 2). However, trees receiving 1 year of weed control (TOOOO) were not significantly larger than those receiving no weed control (OOOOO), and delaying weed control for 2 years (OOTTT) was not detrimental to growth relative to delaying weed control for only 1 year (OTTTT) (Table 2). None of the weed control treatments significantly increased western hemlock fourth-year volume relative to the check (OOOOO), and treatment in the first 2 years seemed to have a negative effect on growth. Only when treatment was delayed for 2 years (OOTTT) in western hemlock was there a significant positive effect on fourth-year diameter relative to no treatment at all (OOOOO).

Although the response to weed control varied greatly between Douglas-fir and western hemlock at Seaside, the response to initial seedling size was similar, as reflected by common slope values that differed little (Table 3) and by nonsignificant interaction effects for volume, diameter, and height when both treatment and initial diameter were included in the model (see Table 1). For both Douglas-fir and western hemlock, fourth-year volume was greater when the largest initial seedling diameters received no weed control (3.46 and 2.44 dm^3, respectively) than when the smallest initial seedling diameters received the most intensive weed control (TTTTT) (2.30 and 1.13 dm^3, respectively) (Fig. 5). Planting Douglas-fir seedlings with the largest initial seedling diameter (9 mm) rather than the smallest (2 mm) increased volume response to weed control (OOOOO vs. TTTTT) by 113% (Fig. 5). With 2 years of weed control (TTOOO), the largest initial diameter planted increased fourth-year volume relative to that of the smallest by 215% in Douglas-fir and 198% in western hemlock (Fig. 5).

Study 2

Both weed control treatment and initial diameter significantly affected 12th-year DBH, height, and volume for Douglas-fir at the Summit and Marcola sites (Table 1). At both sites growth improved with weed control, but response to increasing radius of spot weed control was stronger at Summit than at Marcola (see Table 2). For example, TVC increased volume growth by 336% relative to the check at Summit, but by only 70% at Marcola. Although woody-only control increased 12th-year volume relative to the check by 117% at Summit, this treatment increased volume at Marcola by only 11%, which was not statistically significant.

Not only was response to weed control greater at the Summit site, but response to initial seedling size appeared to be greater as well, with higher common-slope values for both diameter and height at that site (Table 3). The results for the smallest and largest seedlings show that increasing initial seedling diameter increased the volume response to weed control (TVC vs. check) by 160% at Summit and 42% at Marcola (Fig. 6). For the treatment closest to the operational standard in the Pacific Northwest (TVC), the largest initial diameter planted increased 12th-year Douglas-fir volume relative to the smallest by 118% at Summit and 55% at Marcola. Inter-tree competition may be increasing the magnitude of improvement due to seedling size at both 12-year-old study 2 sites.

Table 2. ANCOVA volume, diameter, and height means by site and species for data collected in year 4 at the Sweet Home and Seaside study 1 sites, year 5 at the Blodgett study 1 site, and year 12 at the Summit and Marcola study 2 sites.

Species	Treatment*	Volume† (dm^3)	Diameter (cm)	Height (cm)
Blodgett				
Douglas-fir	OOOOO	2.3c	5.3f	307d
	OOTTT	4.9b	7.4cd	345cd
	OTTTT	6.6a	8.1bc	387ab
	TOOOO	1.8c	4.8f	292e
	TTOOO	3.7b	6.4e	347bc
	TTTOO	3.8b	6.6de	335cd
	TTTTO	7.3a	8.4ab	398a
	TTTTT	8.6a	9.1a	396a
Grand fir	OOOOO	0.4e	3.1f	182d
	OOTTT	1.7c	5.6d	205c
	OTTTT	2.8b	6.8bc	233b
	TOOOO	1.1d	4.4e	214c
	TTOOO	2.1bc	5.9cd	240b
	TTTOO	2.4bc	6.1cd	249ab
	TTTTO	3.9a	7.6b	259a
	TTTTT	5.0a	8.6a	261a
Western hemlock	OOOOO	0.7c	3.4c	225c
	OOTTT	2.4b	5.5b	303b
	OTTTT	4.3a	6.8a	362a
	TOOOO	0.6c	3.3c	224c
	TTOOO	1.6b	4.6b	291b
	TTTOO	2.1b	5.2b	302b
	TTTTO	4.3a	6.7a	365a
	TTTTT	4.3a	6.8a	360a
Western redcedar	OOOOO	0.2c	2.1d	131c
	OOTTT	0.9ab	4.7abc	166bc
	OTTTT	1.7ab	5.6ab	211ab
	TOOOO	0.5bc	3.5cd	169bc
	TTOOO	1.1ab	4.6abc	206ab
	TTTOO	1.0ab	4.4bc	212ab
	TTTTO	2.1a	5.9ab	228a
	TTTTT	2.6a	6.5a	234a
Sweet Home				
Douglas-fir	OOOOO	0.4f	3.1f	154e
	OOTTT	1.3d	5.1d	198d
	OTTTT	2.2bc	6.0c	231c
	TOOOO	0.8e	3.9e	197d
	TTOOO	1.6cd	5.2d	234bc
	TTTOO	2.6ab	6.3bc	258ab
	TTTTO	3.3a	6.8a	270a
	TTTTT	3.2a	6.8ab	269a
Western redcedar	OOOOO	0.0d	1.3e	80c
	OOTTT	0.1cd	1.8de	94bc
	OTTTT	0.3ab	2.9abc	118ab
	TOOOO	0.1bc	2.1cd	128a
	TTOOO	0.2ab	2.5bcd	143a
	TTTOO	0.4a	3.3ab	138a
	TTTTO	0.3ab	3.1ab	127a
	TTTTT	0.5a	3.7a	143a
Seaside				
Douglas-fir	OOOOO	1.8c	5.1d	274a
	OOTTT	3.1ab	6.6abc	267a
	OTTTT	2.8b	6.6bc	248a

Table 2 (*concluded*).

Species	Treatment*	Volume† (dm^3)	Diameter (cm)	Height (cm)
	TOOOO	1.9c	5.4d	258a
	TTOOO	2.6b	6.1c	278a
	TTTOO	3.4ab	7.0ab	265a
	TTTTO	3.7a	7.2ab	277a
	TTTTT	3.8a	7.3a	277a
Western hemlock	OOOOO	1.1abc	4.5bc	249a
	OOTTT	1.6a	5.2a	254a
	OTTTT	1.2ab	4.6abc	246a
	TOOOO	0.8c	3.9c	221a
	TTOOO	0.9b	4.1c	231a
	TTTOO	1.4a	4.9ab	240a
	TTTTO	1.4a	5.0ab	244a
	TTTTT	1.4a	5.0ab	242a
Study 2				
Summit, Douglas-fir	0.375 m^2	62.3bc	14.1bcd	955a
	1.49 m^2	65.9bc	14.5bcd	963a
	3.35 m^2	75.3abc	15.2bc	1012a
	5.95 m^2	86.3ab	16.1ab	1041a
	9.63 m^2 (TVC)	103.8a	17.4a	1083a
	Check	23.8d	9.3e	751b
	Herbaceous	64.9bc	13.8cd	1018a
	Woody	51.6c	12.9d	933a
Marcola, Douglas-fir	0.375 m^2	51.1bc	13.3bc	880bc
	1.49 m^2	56.2ab	13.5ab	929ab
	3.35 m^2	63.1ab	14.1ab	970a
	5.95 m^2	67.4a	14.5a	978a
	9.63 m^2 (TVC)	65.1ab	14.2ab	984a
	Check	38.3d	11.7d	822c
	Herbaceous	66.6a	14.3ab	994a
	Woody	42.5cd	12.3cd	840c

Note: Within sites, species and parameter means followed by the same letters are not different at $\alpha = 0.05$.
*TVC, total vegetation control.
†Volume data were cube-root transformed, except at Sweet Home; back-transformed means are shown. All data at Sweet Home were natural-log transformed; back-transformed means are shown.

With the exception of the check and herbaceous-only treatments, intercept values for diameter and height were remarkably similar between sites (Table 3). Greater response to increasing seedling size accounts for much of the overall increased growth response at Summit, as well as for the greater divergence in 12th-year volume response among treatments with increasing initial seedling diameter (Fig. 6). Also, for the most intense weed control treatments the difference in volume between sites is less at every common level of the covariate than it is on average (Fig. 6, Table 2), suggesting the observed increase in performance at Summit is due in part to larger planting stock (see Fig. 2).

Discussion

Magnitude of the seedling size effect relative to that of weed control

Both seedling size and early weed control had major impacts on the growth of four conifer species through 4, 5, or 12 years. The magnitude of the seedling size effect, which typically goes unreported in vegetation management studies, is clearly large enough to strongly influence the long-term growth and yield of these plots. The relative efficacy of weed control treatments and increased seedling size varied widely among species and sites. At Sweet Home (study 1), for example, ≥2 years of weed control is required for even the largest western redcedar seedlings to achieve fourth-year stem volumes averaging >0.5 dm^3. This response reflects both the high level of weed competition at that site (weed cover in untreated plots was >65% the summer after planting) and the poor competitiveness of western redcedar. In other cases, such as that of western hemlock at Seaside (study 1), even a 2 mm increase in seedling diameter increased volume more than highly intensive weed control, reflecting low levels of weed competition at that site (weed cover in untreated plots was <25% the summer after planting). Finally, in most other cases, multiple combinations of weed control intensity and seedling size would likely result in equivalent volume growth.

Diameter and height growth: additive effects

Effects of herbicide treatments and seedling size were additive for diameter and height. Other researchers have found diameter and height responses to weed control and seedling

Table 3. ANCOVA common-slope and intercept values for diameter and height measured in year 4 at Sweet Home and Seaside, year 5 at Blodgett, and year 12 at Summit and Marcola.

(A) Blodgett, Sweet Home, and Seaside.

	Blodgett						Sweet Home*				Seaside			
	Douglas-fir		Grand fir		Western hemlock		Western redcedar		Western redcedar		Douglas-fir		Western hemlock	
Treatment	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)	ln (diameter) (cm)	ln (height) (cm)	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)
Common slope	0.34	11.4	0.50	8.7	0.57	25.8	0.75	19.4	0.10	0.0884	0.35	12.8	0.40	15.6
Intercept														
OOOOO	3.4	243	1.0	146	1.6	142	–0.6	61.8	–0.1	4.1	3.3	207	3.3	205
OOTTT	5.5	281	3.5	169	3.7	220	2.0	97.0	0.2	4.2	4.8	201	4.1	210
OTTTT	6.2	323	4.7	196	4.9	279	2.9	141.3	0.7	4.4	4.7	182	3.5	202
TOOOO	2.9	228	2.3	178	1.5	142	0.8	99.3	0.4	4.5	3.6	192	2.8	177
TTOOO	4.5	283	3.8	204	2.8	208	1.9	136.2	0.6	4.6	4.2	212	3.0	188
TTTOO	4.7	271	4.0	213	3.4	219	1.7	142.2	0.8	4.6	5.2	199	3.8	197
TTTTO	6.5	333	5.5	223	4.9	282	3.2	158.9	0.8	4.5	5.3	211	3.9	200
TTTTT	7.2	332	6.5	225	5.0	277	3.8	164.4	0.9	4.6	5.5	211	3.8	198

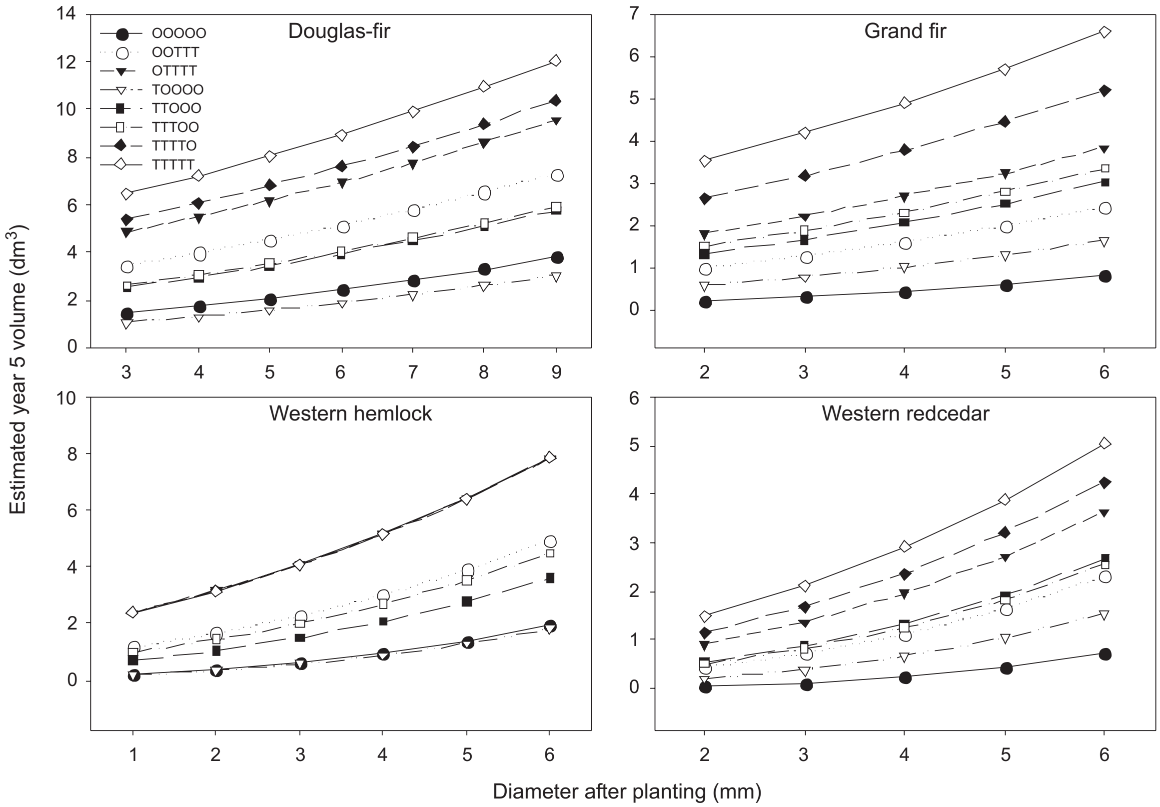
(B) Summit and Marcola.

	Summit		Marcola	
	Douglas-fir		Douglas-fir	
Treatment	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)
Common slope	0.44	0.18	0.28	0.12
Intercept				
0.375 m^2	10.2	7.9	11.5	8.0
1.49 m^2	10.6	8.0	11.7	8.5
3.35 m^2	11.2	8.5	12.3	8.9
5.95 m^2	12.2	8.8	12.7	9.0
Total	13.5	9.2	12.4	9.1
Check	5.4	5.9	9.9	7.4
Herbaceous	9.9	8.6	12.5	9.1
Woody	9.0	7.7	10.5	7.6

Note: Linear model response = (a + b) × initial diameter (mm), where a is the intercept and b is the slope.

*Intercept and slope values for Sweet Home are for the natural log of the response. Douglas-fir is not included at Sweet Home because neither diameter (slope = –0.01, not significant) nor height (slope = –0.85, not significant) was affected by initial diameter.

Fig. 4. Estimated year 5 individual tree volume response to initial seedling diameter by species at the Blodgett study 1 site. Data were back-transformed after cube-root-transformed data were analyzed by using ANCOVA. The OTTTT and TTTTO symbols and lines for western hemlock are behind the TTTTT symbols and lines. Data are presented for all initial diameters observed at least once for each species.



size to be additive in Douglas-fir (Rose and Ketchum 2003), Monterey pine (South et al. 1993*b*), loblolly pine (South et al. 2001*a*), and slash pine (*Pinus elliottii* Engelm.) (South and Mitchell 1999). Mason et al. (1996), however, found a greater increase in Monterey pine height growth with increasing initial diameter when weeds were not controlled. Similarly, Jobidon et al. (2004) found that increases in diameter and height growth resulting from weed-free conditions in black spruce (*Picea mariana* (Mill.) BSP) and white spruce (*Picea glauca* (Moench) Voss) decreased with increasing container stock size, but morphological differences resulting from widely differing fertilization rates used in the production of the different stock sizes (Lamhamedi et al. 1998) may have influenced these results.

Volume growth: synergistic response to weed control and seedling size

The effects of weed control treatments on stem volume increased with increasing initial diameter (a synergistic response), despite additive effects for diameter and height. Because stem volume is a function of the square of diameter × height (eq. 1), the volume increases exponentially across seedling sizes for each treatment in which diameter and height increase linearly. Thus, a significant additive volume response at the cube-root-transformed scale implies a synergistic response at the original scale, the magnitude being greatest in those cases where diameter and height respond strongly to seedling size.

The importance of this synergistic response is that the volume return from increased weed control intensity is greatest for the largest seedlings planted, and conversely, the volume return from increasing seedling size is greatest at the highest weed control intensities. Similar results were obtained by South et al. (1993*b*), who found that volume per hectare response to seedling size in Monterey pine was much greater when total weed control was applied than when the level of weed control was standard. South and Mitchell (1999), however, found that in bare-root slash pine, biomass gains from herbicide treatments fell significantly with increasing root collar diameter at planting, but this response may have been related to increased loss of roots during lifting of larger seedlings. Rose and Ketchum (2003) found no interaction between seedling size and vegetation control in Douglas-fir, but there was little diameter or height response to vegetation control (2 vs. 3 years), making it difficult to distinguish any interactions.

Species and site influences on seedling size responses

Our data also show that the response to seedling size varied both by species and by site. At all three study 1 sites, Douglas-fir response to initial seedling size appeared to be weakest of the four species. In fact, Douglas-fir at Sweet Home did not respond to seedling size at all, whereas western redcedar did strongly. This difference in response, however, may be related to the size of the planting stock used for each species, with Douglas-fir being the only species with

Fig. 5. Estimated year 4 individual tree volume response to initial seedling diameter at the Sweet Home and Seaside study 1 sites. At Sweet Home, western redcedar data were natural-log transformed prior to analysis. At Seaside, data for both species were cube-root transformed prior to analysis. Back-transformed data are shown. Results for Douglas-fir at Sweet Home are not shown because there was no significant volume response to initial seedling diameter. At Seaside, the TTTOO and TTTTO symbols and lines for western hemlock are behind the TTTTT symbols and lines. Data are presented for all initial diameters that were actually observed for at least one seedling

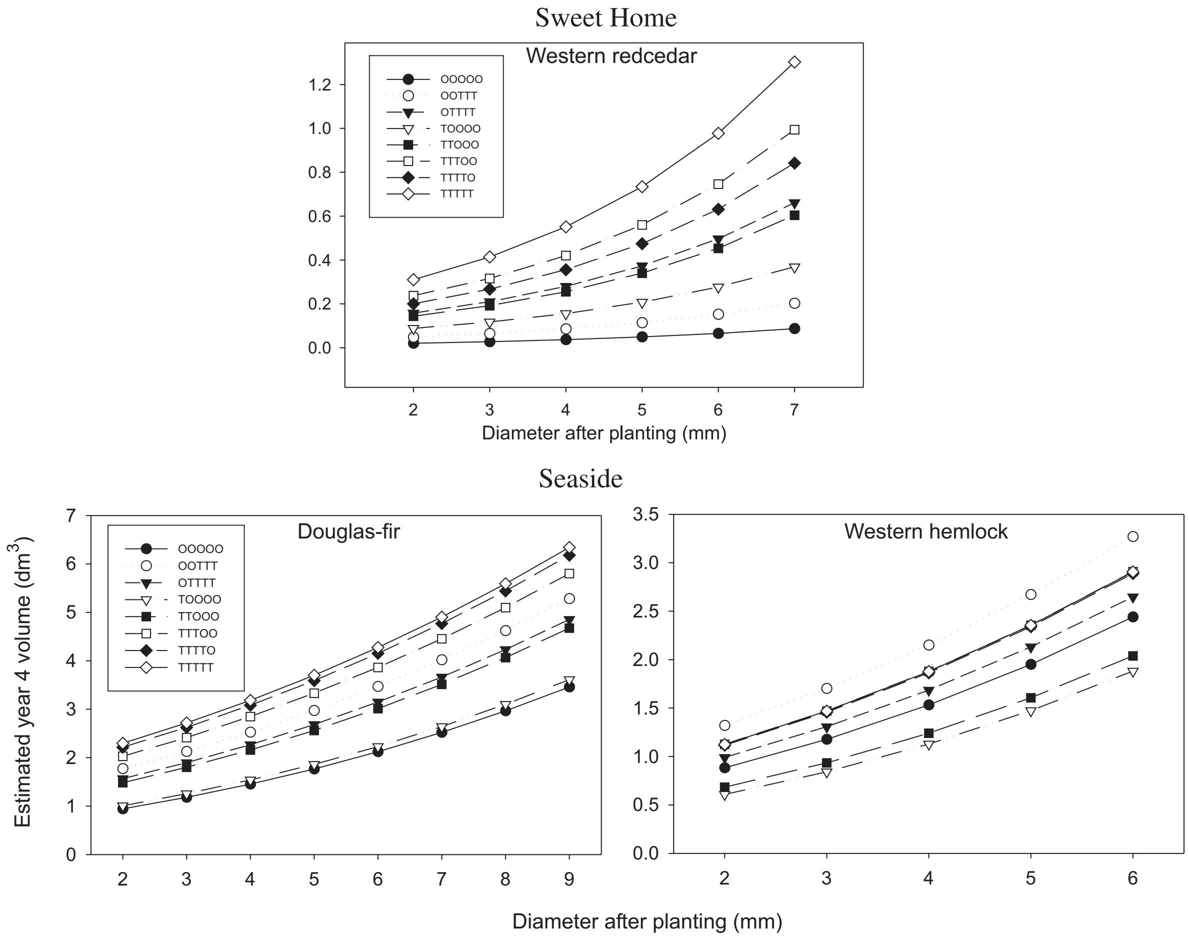
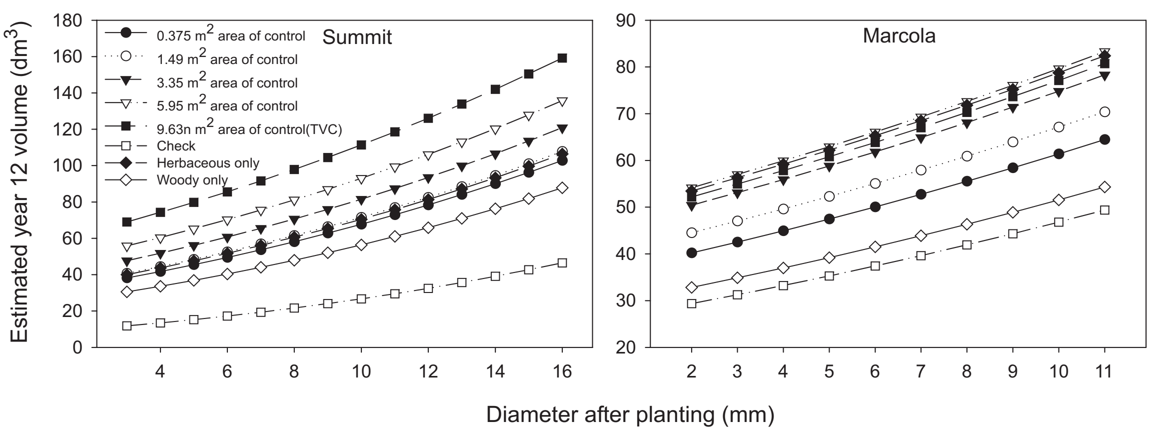


Fig. 6. Estimated year 12 individual tree volume response to weed control treatments and initial seedling diameter in Douglas-fir at the Summit and Marcola study 2 sites. Data were cube-root transformed prior to ANCOVA; back-transformed data are shown.



seedling diameters ≥7 mm. Differences in response to seedling size may be especially pronounced in stock encompassing a smaller range of sizes, especially in the case of less competitive species, such as western hemlock and western redcedar. Douglas-fir response to bare-root seedling size also varied by site in study 2, with greater response to seedling size at the Summit site than at the Marcola site. Interestingly, planting stock at Summit was larger than that at

Marcola (see Fig. 3), so factors other than relative size range may be of primary importance in determining the response to increased seedling size in bare-root stock. The site index at Summit (41 m) is only slightly higher than that at Marcola (37 m), but this difference, in addition to better weed control efficacy at Summit, may have increased resource availability, allowing larger seedlings to take advantage of their increased growth potential.

Economic considerations

Our analytical approach has several limitations. First, the nature of these studies precludes a comparative cost–benefit analysis for weed control and seedling size effects. Not only were many of the ground-based herbicide treatments in these studies more intensive and expensive than typical operational treatments, but seedlings are not usually purchased by diameter — rather, they are purchased by stock type (encompassing a range of diameters). Therefore, it would be unrealistic to assign a cost to each seedling size and each herbicide treatment. Second, although our results show that volume growth in the largest seedlings within a lot increases more in response to weed control than it does in the smallest seedlings, we could not evaluate whether the best way to take advantage of this effect would be to cull a high percentage of the smallest seedlings or to increase seedling size overall by planting larger stock types. Both approaches will increase seedling cost, and increased culling also has the potential to alter the genetic makeup of the stand (Campbell and Sorensen 1984). The above considerations in no way nullify the fact that there may be a very clear economic gain to be had by planting larger stock. The figures in this study clearly demonstrate a positive synergistic effect when weeds are controlled in the growing space of large-diameter seedlings. The increase in volume correlates with an increase in value.

Weed control and seedling size treatments are often at least partially exchangeable (Örlander et al. 1990; South et al. 1993*b*). This implies that growth and survival targets can usually be met by planting small trees with intensive weed control or larger trees with less intensive weed control. The optimum combination of treatments is the one that can achieve these targets at the lowest overall cost. In the past, there has been a mindset to minimize seedling costs and shift resources into intensive silvicultural treatments to boost productivity (South et al. 2001*b*), an approach that has been proven economically unsound across a wide range of species (South et al. 1993*a*).

In recent years, seedling stock types in the Pacific Northwest have increased in size substantially. Bare-root stock types that involve transplanting 1-year-old bare-root (1 + 1) or 1-year-old container (plug + 1) seedlings into a transplant bed at wide spacings have replaced the smaller 2 + 0 stock type, and 250 mL (15 in.^{3}) container stock types are replacing 164 cm^3 (10 in.^{3}) containers as the norm. This shift indicates an upward movement in productivity targets rather than a movement of resources from weed control into planting stock. This constant improvement in productivity due to improved vegetation management strategies and tools, in addition to improved seedling size and quality, makes it difficult to define targets, let alone determine the most cost-effective approach to achieving them. This study should lead the way to implementation of the results of studies that use recent advances in weed control technology and increases in stock size to quantify long-term consequences of synergistic interactions and to determine the optimal partitioning of resources between weed control and seedling stock size.

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References

Biring, B.S., Comeau, P.G., and Fielder, P. 2003. Long-term effects of vegetation control treatments for release of Engelmann spruce from a mixed-shrub community in southern British Columbia. Ann. For. Sci. **60**(7): 681–690.

Bruce, D., and DeMars, D.J. 1974. Volume equations for second-growth Douglas-fir. USDA For. Serv. Res. Note PNW-239.

Campbell, R.K., and Sorensen, F.C. 1984. Genetic implications of nursery practices. *In* Forest nursery manual: production of bareroot seedlings. *Edited by* M.L. Duryea and T.D. Landis. Martinus Nijhoff – Dr. W. Junk, The Hague, Netherlands. pp. 183–192.

Harrington, T.B., Wagner, R.G., Radosevich, S.R., and Walstad, J.D. 1995. Interspecific competition and herbicide injury influence 10-year responses of coastal Douglas-fir and associated vegetation to release treatments. For. Ecol. Manage. **76**: 55–67.

Jobidon, R., Roy, V., and Cyr, G. 2004. Net effect of competing vegetation on selected environmental conditions and performance of four spruce seedling stock sizes after eight years in Quebec (Canada). Ann. For. Sci. **60**: 691–699.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Research Center, Centralia, Wash. Weyerhaeuser Forestry Paper 8.

Lamhamedi, M.S., Bernier, P.Y., Hébert, C., and Jobidon, R. 1998. Physiological and growth responses of three sizes of containerized *Picea mariana* seedlings outplanted with and without vegetation control. For. Ecol. Manage. **110**: 13–23.

Long, A.J., and Carrier, B.D. 1993. Effects of Douglas-fir 2 + 0 seedling morphology on field performance. New For. **7**: 19–32.

Mason, E.G. 2001. A model of juvenile growth and survival of *Pinus radiata* D. Don: adding the effects of initial seedling diameter and plant handling. New For. **22**: 133–158.

Mason, E.G., South, B., and Weizhong, Z. 1996. Performance of *Pinus radiata* in relation to seedling grade, weed control, and soil cultivation in the central North Island of New Zealand. N.Z. J. For. Sci. **26**: 173–183.

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

Newton, M., Cole, E.C., and White, D.E. 1993. Tall planting stock for enhanced growth and domination of brush in the Douglas-fir region. New For. **7**: 107–121.

Oester P.T., Emmingham, W., Larson, P., and Clements, S. 1995. Performance of ponderosa pine seedlings under four herbicide regimes in northeast Oregon. New For. **10**: 123–131.

Oppenheimer, M.J., Shiver, B.D., and Rheney, J.W. 1989. Ten-year growth response of midrotation slash pine plantations to control of competing vegetation. Can. J. For. Res. **19**: 329–334.

Örlander, G., Gemmel, P., and Hunt, J. 1990. Site preparation: a Swedish overview. Forestry Canada – British Columbia Ministry of Forests, Victoria. FRDA Rep. 105.

Perry, M.A., Mitchell, R.J., Zutter, B.R., Glover, G.R., and Gjerstad, D.H. 1993. Competitive responses of loblolly pine to gradients in loblolly pine, sweetgum, and broomsedge densities. Can. J. For. Res. **23**(10): 2049–2058.

Puértolas, J., Gil, L., and Pardos, J.A. 2003. Effects of nutritional status and seedling size on field performance of *Pinus halepensis* planted on former arable land in the Mediterranean basin. Forestry, **76**(2): 159–168.

Ritchie, G.A., Tanaka, Y., Meade, R., and Duke, S.D. 1993. Field survival and early growth of Douglas-fir rooted cuttings: relationship to stem diameter and root system quality. For. Ecol. Manage. **60**: 237–256.

Rose, R., and Ketchum, J.S. 2003. Interaction of initial seedling diameter, fertilization and weed control on Douglas-fir growth over the first four years after planting. Ann. For. Sci. **60**: 1–11.

Rose, R., and Rosner, L.S. 2005. Eighth-year response of Douglas-fir seedlings to area of weed control and herbaceous versus woody weed control. Ann. For. Sci. **62**: 481–492.

Rose, R., Ketchum, J.S., and Hanson, D.E. 1999. Three-year survival and growth of Douglas-fir seedlings under various vegetation-free regimes. For. Sci. **45**: 117–126.

SAS Institute Inc. 1989. SAS/STAT user's guide. Version 8.2. 4th ed. Vol. 11. SAS Institute Inc., Cary, N.C.

South, D.B., and Mitchell, R.J. 1999. Determining the "optimum" slash pine seedling size for use with four levels of vegetation management on a flatwoods site in Georgia, U.S.A. Can. J. For. Res. **29**: 1039–1046.

South, D.B., Mitchell, R.J., Zutter, B.R., Balneaves, J.M., Barber, B.L., Nelson, D.G., and Zwolinski, J.B. 1993*a*. Integration of nursery practices and biological potential for improving regeneration. Can. J. For. Res. **23**: 2083–2092.

South, D.B., Zwolinski, J.B., and Donald, D.G.M. 1993*b*. Interactions among seedling diameter grade, weed control, and soil cultivation for *Pinus radiata* in South Africa. Can. J. For. Res. **23**: 2078–2082.

South, D.B., Zwolinski, J.B., and Allen, H.L. 1995. Economic returns from enhancing loblolly pine establishment on two upland sites: effects of seedling grade, fertilization, hexazinone, and intensive soil cultivation. New For. **10**: 239–256.

South, D.B., Rakestraw, J.L., and Lowerts, G.A. 2001*a*. Early gains from planting large-diameter seedlings and intensive management are additive for loblolly pine. New For. **22**: 97–110.

South, D.B., Rose, R.W., and McNabb, K.L. 2001*b*. Nursery and site preparation interaction research in the United States. New For. **22**: 43–58.

Stein, W.I. 1995. Ten-year development of Douglas-fir and associated vegetation after different site preparation on coast range clearcuts. USDA For. Serv. Res. Pap. PNW-RP-473.

van den Driessche, R. 1992. Absolute and relative growth of Douglas-fir seedlings of different sizes. Tree Physiol. **10**: 141–152.