Survival and Growth of Douglas-Fir Relating to Weeding, Fertilization, and Seed Source

Brian E. Roth *and* **Michael Newton,** *Department of Forest Science, Oregon State University, Corvallis, OR 97331.*

ABSTRACT. *The goal of this study was to quantitatively evaluate the individual and interactive effects of weed control, nitrogen fertilization, and seed source on Douglas-fir* (Pseudotsuga menziesii) *survival and growth in a range of sites and growing conditions in western Oregon. Weed control was the dominant factor influencing seedling survival and growth and accounted for 49% of the explained variation in seedling volume after 2 yr. Nitrogen fertilization had no effect when used in conjunction with weed control and a negative effect when used without weed control. Seedlings from a seed orchard source were significantly larger in diameter and volume than those from a wild local source after two growing seasons, but second-year heights were similar for the two seedling types. Initial seedling size was positively correlated with growth rate. West. J. Appl. For. 11(2):00–00.*

Douglas-fir survival and growth in western Oregon is limited by competition from associated vegetation for limited site resources (Zedaker 1981, Wagner 1989), and can be further reduced by the pressures of deer browse (Hartwell 1973). Silviculturists can manipulate site conditions through vegetation control and/or fertilization to increase seedling growth and survival. Planting stock selection (size) can also affect seedling growth and survival (Newton et al. 1993).

Numerous prior studies have examined the effects of weed control, soil fertilization, and seed source individually and in combination. Only one has examined effects of all three treatments interactively (Brown 1970); this study demonstrated a three-way interaction in *Pinus sylvestris* L. seedlings among seed provenance, soil fertility, and soil moisture level, with the latter most affecting seedling growth.

The objective of this study was to quantify the effects and determine the relative importance of weed control, nitrogen fertilization, and seed source, including any interactions, on the survival and growth of Douglas-fir outplants in a range of site conditions. To accomplish this objective, we used factorial experiments on three sites that evaluated survival and growth of comparably sized genetically selected or local wild Douglas-fir nursery stock with and without heavy herb competition and with and without nitrogen fertilization.

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Study Sites

We conducted the study in the central Oregon Coast Range, in Benton County west of Corvallis, Oregon (44°N, 123°W), an area characterized by warm winters with heavy precipitation and warm dry summers. The three study sites, which collectively span much of the range of Douglas-fir productivity in this area, included: (1) a relatively droughty Willamette Valley site in Oregon State University's McDonald Research Forest, (2) a moderately productive forest site in the Willamette Valley foothills, in Oregon State University's Paul M. Dunn Research Forest, and (3) a highly productive site in the mid-Coast Range near Summit, Oregon, on property belonging to Starker Forests, Inc. Table 1 lists the site characteristics. The Dunn Forest and Summit sites were in recently harvested Douglas-fir stands. The McDonald Forest site was on abandoned state nursery beds now fully occupied by a combination of exotic and native grasses and herbs as well as patches of Himalaya blackberry (*Rubus procerus* Muell.). Herbs, grasses, and ferns (*Polystichum munitum* and *Pteridium aquilinum*) were the main forms of associated vegetation on all sites and were consistent within sites (Table 2). The soil on all sites was of silty clay loam types, but among the sites it varied by series. The McDonald Forest soil was of the Bellpine series, derived from Spencer sandstone, and was covered with 20 cm off-site loam. The dense cover was mostly mixed grasses. The Dunn Forest soil was of the Price-

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Table 1. General site descriptions (fertility data recorded prior to fertilization).

Site	Elevation	Annual precipitation (Johnsgard 1963)	% Soil N	% Soil P	Douglas-fir SI_{100} (Knezevich 1975)	Dominant cover
McDonald Forest	120 m	945 mm[a]	0.137	0.095	42 m	Perennial grasses, Himalaya blackberry
Dunn Forest	185 m	1270 mm[a]	0.202	0.083	48 m	Bigleaf maple sprouts, sword fern
Summit	365 m	1905 mm	0.290	0.111	55 m	Bigleaf maple sprouts, sword fern, bracken

[a] Summer moisture deficit often exceeds 325 mm (Johnsgard 1963).

Ritner complex, derived from Siletz River basalts. The Summit soil was associated with the Apt series, derived from Tyee sandstone/siltstone (Knezevich 1975).

Materials and Methods

Experimental Design

The experimental design was a randomized complete block, 2^3 factorial, with three replicates at each site for a total of 9 blocks and 72 plots. The 8 treatments created by the factorial design were randomly assigned to 3.6 m × 11.0 m plots within each block, with an untreated buffer strip at least 2.0 m wide between adjacent plots. Plots were grouped into blocks in an approximate 2 × 4 arrangement within areas of similar initial conditions. On steep slopes where an environmental gradient was likely, the blocks were oriented perpendicular to the slope and parallel to each other to minimize plot to plot variation within blocks while maximizing variation among blocks (Steel and Torrie 1980).

The three factors in the experiment were weed control (complete W_1 vs. none W_0), nitrogen fertilization (used F_1 vs. not used F_0), and seed source (seed orchard S_1 vs. wild local S_0). The experimental unit was the mean of 28 seedlings on each plot. The entire experiment was repeated with three replications on each site.

Table 2. Common plant species associated with the three sites.[1]

Common name	Scientific name	Site[b]		
Woody species				
Bigleaf maple	*Acer macrophyllum* Pursh		2	
Himalaya blackberry	*Rubus procerus* Muell.	1		
Salal	*Gaultheria shallon* Pursh			3
Snow-berry	*Symphoricarpos albus* (L.) Blake			3
Ocean spray	*Holodiscus discolor* (Pursh) Maxim			3
Western hazel	*Corylus cornuta* Marsh		2	3
Wild blackberry	*Rubus ursinus* Cham. & Schlech		2	
Herbs				
Bedstraw	*Galium* sp.		2	3
Bull thistle	*Cirsium vulgare* (Savi) Tenore	1	2	3
Canada thistle	*Cirsium arvense* (L.) Scop.	1	2	3
Clover	*Trifolium* sp.		2	
Common daisy	*Erigeron* sp.		2	
Dove's foot geranium	*Geranium molle* L.			3
False spikenard	*Smilacina racemosa* (L.) Desf.			3
Woodland groundsel	*Senecio sylvaticus* L.			3
Groundsel	*Senecio vulgaris* L.		2	
Lotus	*Lotus* sp.			3
Pathfinder	*Adenocaulon bicolor* Hook.			3
Purple iris	*Iris tenax* Dougl.		2	3
Sheperd's purse	*Capsella bursa-pastoris* (L.) Moench		2	
Sow-thistle	*Sonchus oleraceus* L.		2	
Star-flower	*Trientalis latifolia* Hook.			3
Sweet colt's foot	*Petasites frigidus* (L.) Fries		2	
Tansy ragwort	*Senecio jacobaea* L.			3
Vari-leaved collomia	*Collomia heterophylla* Hook.			3
Wild carrot	*Daucus carota* L.	1	2	
Wild ginger	*Asarum caudatum* Lindl.			3
Wild pea	*Vicia americana* Muhl.		2	
Wind-flower	*Anemone* sp.			3
Wood nemophila	*Nemophila parviflora* Dougl.		2	
Yarrow	*Achillea millefolium* L.	1		
Ferns				
Sword-fern	*Polystichum munitum* (Kaulf.) Presl		2	3
Western bracken	*Pteridium aquilinum* (L.) Kuhn			3
Grasses				
Reed's canary grass	*Phalaris arundinacen* L.	1		
Ripgut grass	*Bromus rigidus* Roth	1		
Velvet grass	*Holcus lanatus* L.	1	2	3

[a] Nomenclature after Gilkey and Dennis (1980), Hitchcock (1971).
[b] Site: 1 = McDonald Forest, 2 = Dunn Forest, 3 = Summit.

Seedling Sources

The Douglas-fir plug-1 transplants used for this study were grown from two seed sources: genetically improved and local wild seed collections. The genetically improved seed was developed by the Burnt Woods Tree Improvement Cooperative at the J.E. Schroeder seed orchard, near St. Paul, OR. This seed was derived from open-pollinated crosses among progeny of 161 superior trees located within the same seed zone (252) as the local wild source. The seed orchard stock was grown at the Industrial Forestry Association (IFA) nursery in Toledo, WA. The local wild seed was collected from within seed zone 252 and did not represent any level of genetic selection. Nursery stock from this seed source was not available from the IFA nursery in Toledo, so the wild plug-1 transplants were obtained from the D.L. Phipps State Nursery, near Elkton, OR. Hence, there was some possibility of confounding between genetics and nursery regime. However, the size ranges of seedlings from both nurseries were similar, averaging 54 cm ht × 6 mm diam at 15 cm above ground.

Treatments

All seedlings were planted within 1 wk of each other in February 1992; each plot contained 28 seedlings at a spacing of 0.5 m × 1.0 m. Planting was done block by block and site by site. To accomplish complete weed control, 1.37 kg/ha hexazinone (Velpar L®) herbicide was broadcast applied after planting, at a volume rate of 92 l/ha, with a handheld 3.6 m boom powered by a pressurized backpack sprayer. Reinvading herbs in the weeded plots were controlled in the subsequent year with directed spot applications. Nitrogen fertilizer was applied by broadcasting 220 kg/ha urea prill (46-0-0) with a handheld rotary dispenser in a 3.6 m swath. Fertilizer and weeding treatments were performed on March 18, 1992, and again on March 25, 1993. On each site, an electrically charged 18 gauge wire, suspended 1.0 m off the ground with fiberglass poles, was wound among all plots to discourage deer browsing. The wires were electrified during May and June of each year with a Jolt electric fence controller (model 4000B, IAAB U.S.A., Inc., Bellevue, WA). To prevent wire short circuiting, vegetation growing beneath the wire was controlled with a single directed application of glyphosate in the spring of each year. Care was taken to avoid treating unweeded plot vegetation in this process.

Measurements

Douglas-Fir and Cover Measurements

Seedlings were measured shortly after planting (spring 1992) and at the end of each growing season (August 1992, 1993). Measurements included seedling height (nearest cm), diameter at 15 cm (nearest mm), and vigor. Vigor, a qualitative measure, was quantified on a five-point scale (1 = most vigorous, 5 = dead) based on seedling color and general appearance. From the height and diameter measurements, stem volume was estimated by using the formula for a cone:

$$\text{Volume} = \pi \times d^2 \times h / 12$$

where

d = diameter at 15 cm

h = total height

Volume, diameter, and height increments were calculated at the end of each growing season from yearly differences in seedling dimensions. Occurrences of deer browse, lammas growth, and herbicide damage were also noted in the fall of each year.

Percent cover by herbaceous forbs and grasses was estimated on a half-meter radius around each seedling in the fall of 1992; in the fall of 1993, because of the relative homogeneity of the vegetation within the plots, it was estimated as a percentage of total plot area. Percent overtopping was calculated with the cone occlusion method described by Howard and Newton (1984).

Xylem Water Potential and Soil Moisture

Predawn and midday xylem water potentials were measured with a Scholander pressure chamber (Waring and Cleary 1967, Ritchie and Hinckley 1975) from current-year shoots of three randomly selected seedlings per plot. These measurements were made in mid-July 1992 and mid-August 1993 to obtain maximum contrast in water regimes between weeded and unweeded treatments. In 1992, plot soil moisture was measured gravimetrically at the time of the xylem water potential measurements; soil moisture was not measured in 1993 because of an abnormally wet summer.

Nutrient Content

A baseline analysis of mineral soil nitrogen and phosphorus was done for each site at the time of planting (February, 1992) by using a composite of six subsamples taken from the top 30 cm of mineral soil at each site. Total foliage nitrogen and phosphorus were measured as per Bremner and Mulhaney (1982) for each treatment and site at the end of the second growing season (October 1993). In order to make these measurements, foliage samples were taken from the current year's growth of an upper whorl lateral, excluding any lammas shoots, on the southeast side of each surviving seedling. These samples were bulked by treatment across blocks on each site for a total of 24 samples. In order to determine whether nitrogen fertilization resulted in dilution of at least one other macronutrient, total nitrogen and phosphorus were determined with a standard micro-kjeldahl digestion method, with nutrient concentrations calculated on a dry weight basis (Lavender 1970).

Statistical Treatment

Seedling diameter and vigor data were transformed using natural logarithms to approximate normality and constant variance. Some additional variables, based on probability, were transformed by the arcsine square root (Sabin and Stafford 1990). Treatment ANOVAs were carried out by using plot averages weighted by the number of surviving seedlings in each plot. Differences in response were subjected to analysis of covariance (ANCOVA) for main and interaction effects according to the following model (Steel and Torrie 1980):

$$Y_{ijklm} = m + L_i + B(L)_{ij} + W_k + F_l + WF_{kl} + S_m + WS_{km} + FS_{lm} + WFS_{klm} + LW_{ik} + LF_{il} + LWF_{ikl} + LS_{im} + LWS_{ikm} + LFS_{ilm} + b(X_{ijklm} - c..) + LWFS_{iklm}$$

where

L	= site (i = 1,2,3)
B	= block (j = 1,2,3)
$B(L)$	= error (a) (blocks within sites)
W	= weed control (k = 0,1)
F	= fertilizer (l = 0,1)
S	= seed source (m = 0,1)
$b(X_{ijklm} - \chi..)$	= covariate denoted by X
$LWFS$	= error *(b)*.

Site terms were tested against error *(a)*; all remaining terms were tested against error *(b)*. When a significant covariate was not found, the covariate term was omitted from the model. Significant differences between means were determined by using Bonferroni's protected Least Significant Difference (LSD) procedure (Milliken and Johnson 1984).

Foliar nitrogen and phosphorus data were analyzed by ANOVA with the following model:

$$Y_{ijkl} = m + L_i + W_j + F_k + WF_{jk} + S_l + WS_{jl} + FS_{kl} + WFS_{jkl} + LWFS_{ijkl}$$

where

L	= site (i = 1,2,3)
W	= weed control (j = 0,1)
F	= fertilizer (k = 0,1)
S	= seed source (l = 0,1)
$LWFS$	= error *(a)*.

All terms in the model were tested against error *(a)*.

Multiple linear regression models were developed on an individual seedling basis to relate seedling survival, size, growth, and vigor to the various combinations of weed control, fertilization, and initial seedling dimensions represented by the various treatments. The models explaining the most variance were selected with the stepwise procedure described by Neter et al. (1989). Several seedlings at the Dunn Forest and Summit sites showed signs of herbicide damage in the second growing season and were eliminated from the analysis. As a result, second-year survival is reported only for the McDonald site on the assumption that an undetermined percentage of mortality on other sites was caused by second-year spot residues of hexazinone.

Results

Weed Control

Weeding (as compared with no weeding) made a highly significant, positive difference in seedling survival, growth, vigor, and xylem water potentials ($P < 0.001$), as well as in plot soil moisture ($P < 0.0001$). Alone, weeding accounted for 49% of all explained variation in seedling volume at age 2 (Figure 1) and for similar percentages of variation in the other growth parameters. Table 3 illustrates the relatively strong effect of weed control on seedling growth compared with the two other experimental factors. Among sites, weeding effects varied in degree of significance. For example, weed control improved stem volume increment most significantly on the best growing site (Summit), although that was not where the greatest increase in relative growth occurred. Survival was improved most significantly on the poorest growing site (McDonald Forest) (Table 4).

Fertilization

Fertilization significantly increased the average foliar nitrogen concentration in both years, but had no effect on foliar phosphorus concentrations. It reduced seedling survival and predawn xylem water potentials in the first year, especially on unweeded plots. Second-year height and height growth were significantly ($P < 0.05$) less in fertilized plots than in unfertilized plots (Table 3), especially in unweeded

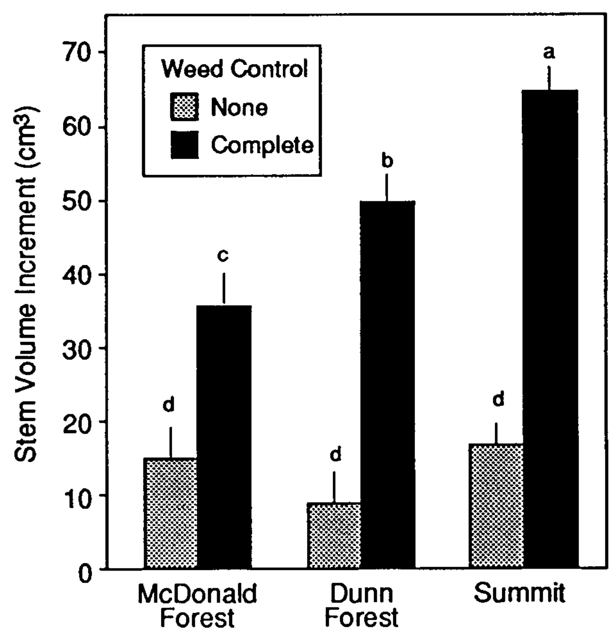

Figure 1. Site × weed control interaction for stem volume increment after 2 growing seasons. Vertical lines above bars represent one standard error. Bars with the same letter are not significantly different at the 95% confidence level using Bonferroni's LSD.

Table 3. Means for second-year growth data by main effect (no main interactions were significant).

	Weed control			Fertilization			Seed source		
	W_1	W_0	% diff	F_1	F_0	% diff	S_1	S_0	% diff
Height[a] (cm)	82.5	68.9	19.7[b]	74.1	77.3	−4.1[c]	77.0	74.4	3.4
Height increment (cm)	27.9	16.1	73.3[b]	20.5	23.5	−12.8˙	23.2	20.8	11.5
Diameter (mm)	15.9	10.7	48.6[b]	13.1	13.5	−2.5	14.1	12.5	12.8[b]
Diameter increment (mm)	7.0	2.7	259.3[b]	4.6	5.1	−9.8	5.1	4.5	13.3˙
Height:Diameter	5.3	6.7	−20.9[b]	6.0	6.0	0.0	5.8	6.1	−4.9[d]
Volume[e] (cm^3)	49.5	18.6	266.1[b]	28.7	32.1	−10.6	35.5	25.9	37.1[b]
Volume increment (mm^3)	50.1	13.4	373.9[b]	30.3	33.2	−8.9	36.6	26.9	36.1[b]

[a] Adjusted for initial seedling height.
[b] $P < 0.001$.
[c] $P < 0.05$.
[d] $P < 0.01$.
[e] Back transformed from the natural log.

plots. On sites with high soil nitrogen (Dunn Forest and Summit), second-year seedling diameter growth tended to be less in fertilized plots than in unfertilized plots (Figure 2).

In the first year, there was significant ($P < 0.05$) negative interaction between fertilization and weed control. Fertilization increased competition to the extent that survival and growth on unweeded plots were reduced more than on plots with little cover (Figure 3).

Seed Source

First-year seedling diameter and volume were significantly larger for the seed orchard seed source than for the wild local seed source after accounting for initial diameter and volume. By the end of the second year, the seed orchard seedlings were larger and faster growing in diameter and volume than the wild seedlings (Table 3), but the difference had decreased in degree of mean separation. Seed source had no effect on seedling height, but the seed orchard seedlings had a lower height-to-diameter ratio than the wild seedlings after accounting for the initial height-to-diameter ratio. Seedlings from the seed orchard source showed greater vigor than the wild seedlings. There was no interaction between seed source and weed control or fertilization, indicating that the gains from the seed orchard source were additive.

Role of Initial Diameter and Overtopping Competitors

The response models (Figure 4) regressing seedling xylem water potential against estimated cover and overtopping associated increasing seedling stress with increasing levels of herbaceous competition. The models describing second-year seedling height and diameter associated initial seedling dimension with seedling size over time. Although volume was associated with initial seedling diameter in the response models, a stronger, and negative, volume association was

Table 4. First-year survival by site and weed control treatment.[a]

Site	Weed control treatment: Complete	None
McDonald Forest	96.8 a	58.7 b
Dunn Forest	95.3 a	60.9 b
Summit	96.6 a	92.3 a

[a] Across rows, means followed by the same letter are not significantly different at the 95% confidence level using Bonferroni's adjusted LSD.

with overtopping vegetation, which was also found to reduce seedling diameter growth while increasing seedling height-to-diameter ratio. Average predawn moisture stress explained most of the variation in the other growth variables.

First-year seedling height growth was dependent on an interaction between browsing and lammas growth, which is discussed elsewhere (Roth and Newton, in preparation). Second-year height was negatively affected by the deer browse in the second growing season.

Discussion

It is routine to observe benefits of weeding. Our observations here put weeding into perspective with other contributions of intensive culturing. This experiment evaluated weed control, nitrogen fertilization, and seed source in a factorial design that identified the partial contributions of each. Weed control (i.e., absence of competing cover) proved substantially to be the dominant factor; it influenced all components of seedling survival and growth measured, to a much greater degree than the two other factors. This finding is consistent with other similar facto-

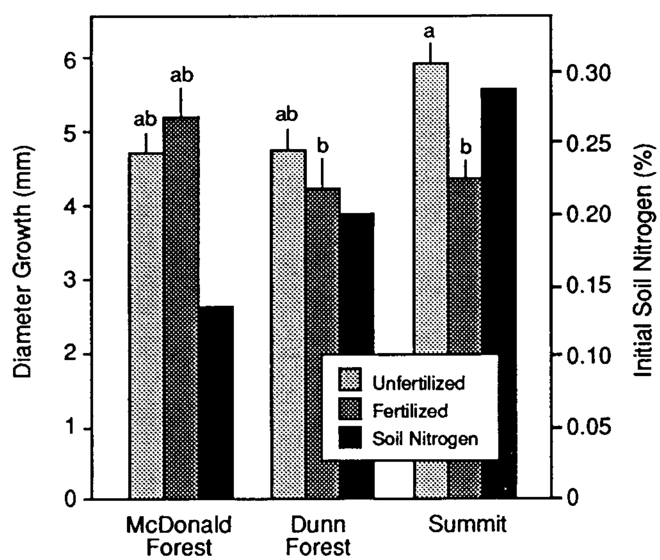

Figure 2. Second-year diameter increment demonstrating site × fertilizer interaction. Vertical lines above bars represent one standard error. Bars with the same letter are not significantly different at the 95% confidence level using Bonferroni's LSD.

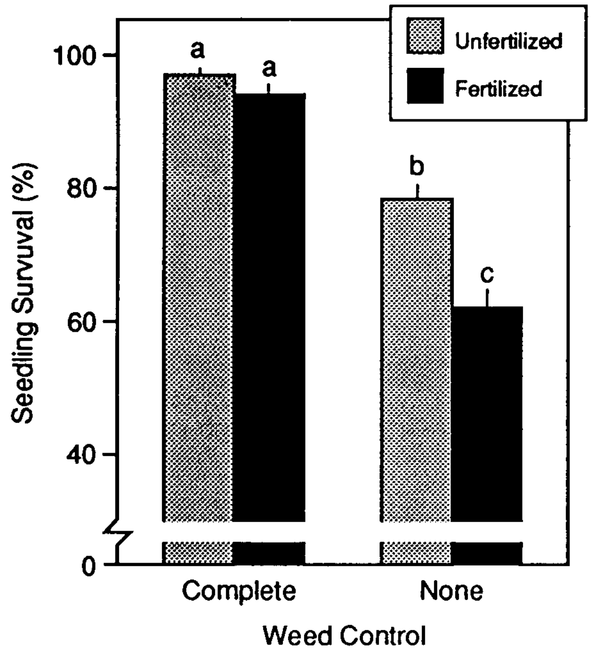

Figure 3. First-year survival demonstrating weed control × fertilization interaction. Vertical lines above bars represent one standard error. Bars with the same letter are not significantly different at the 95% confidence level using Bonferroni's LSD.

rial experiments in which one factor proved dominant (Reed et al. 1983, Brand and Janus 1988).

Weed Control

Weed control increased seedling survival and growth rates by reducing the amount of associated vegetation and thereby conserving soil moisture. This supports the work of Newton and Preest (1988), Sands and Nambiar (1984), and Nambiar and Zed (1980). Seedling diameter was most sensitive to overtopping vegetation (Figure 4). Seedling height and volume were most responsive to predawn xylem water potential (φ), which was related to weeding. This is supported

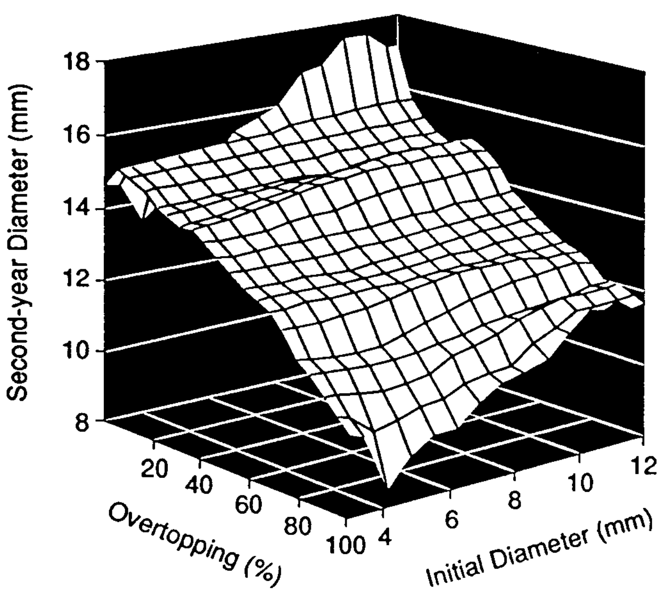

Figure 4. Response surface for second-year stem diameter vs. percent overtopping and initial diameter.

by Eissenstat and Mitchell (1983) and Chan (1984) who found that Douglas-fir seedling diameter was a sensitive indicator of competition, especially overtopping. Newton and Preest (1988) showed xylem water potential to be related to all seedling growth parameters. Conservation of water is related to effective length of growing season in summer-dry climates. Mobility of nutrients is related to abundance of soil solutions. Waring (1972), Brand and Janus (1988), and Sutton (1975) speculated that the positive effect of vegetation control on foliar nitrogen was related to the uptake of nutrients not utilized by the vegetation (i.e., removal of a dominant sink). Removal of cover that depletes water and hence immobilizes nutrients also prevents light interception. Thus, weed control contributes to each class of resource. Gains in absolute stem volume growth were the greatest on the best sites and where the weeds were controlled. The good survival seen on the Summit site reflects both the greater rainfall on that site and the greater summer cloud cover with reduced water demand. Moreover, the total first-year herb density was least on that site because of the closed-canopy nature of the preceding stand and the short time between harvest and time of planting.

Fertilization

The negative effect of nitrogen fertilization is probably due to the greater ability of weeds to benefit from nitrogen, compared with conifers. These sites typically do not show nitrogen deficiencies during the seedling stage (Newton, unpublished observations). Nitrogen increased overtopping and soil moisture depletion in relation to increased weed density. Others have reported similar seedling responses to fertilization (Smith et al. 1966, Walters et al. 1966, Brockley 1988) and have noted the same interaction effects between weeding and fertilization. Waring (1972) found that the effects of fertilization depend on the degree to which vegetation is controlled; Waring (1972) and Squire (1977) both observed that fertilization can stimulate growth of associated vegetation, leading to accelerated depletion of available soil moisture.

The lack of seedling response to fertilization on the weeded plots was unexpected. Even though fertilization increased foliar nitrogen concentrations, the absolute growth rates of fertilized seedlings were lower than those for unfertilized seedlings. Concentrations in weeded plots were presumably all within the plateau of maximum growth. We also observed that as foliar nitrogen concentrations increased, phosphorus concentrations decreased. Van den Driessche (1980) found a similar phosphorus depression pattern in a nursery trial with Douglas-fir. Gill and Lavender (1983) found a poor growth response of urea-fertilized western hemlock in the Coast Range of Oregon; although foliar nitrogen content was significantly increased, the concentrations of phosphorus, calcium, magnesium, manganese, iron, aluminum, and boron were reduced. In our study, although foliar phosphorus concentrations decreased as nitrogen levels increased, both remained within the range considered by Landis (1985) to be adequate for seedling growth. Therefore, the lack of response to the nitrogen treatment may instead have been due (a) to lack of deficiency, or (b) to a change in soil chemistry due to the pH effects of the fertilizer, which in turn influenced the form of nitrogen or availability of other nutrients in the soil (Otchere-Boateng and Ballard 1978). The NH_4^+ form of nitrogen is rapidly accumulated in seedlings, and at high concentrations can result in reduced growth or death (Schaedle 1991). Gill (1981) found that adding urea to western hemlock stands altered the soil pH enough to damage the mycorrhizal roots. Elevated pH resulted in increased NH_4^+ and NO_3^- concentrations and decreased amounts of calcium, magnesium, and potassium.

Seed Source

In this study the true genetic effect could not be quantified because of confounding between the seed sources and the different nurseries in which the seedlings were grown. However, seed source (or possibly nursery cultural regime) did influence seedling growth rates in an additive manner to the other experimental factors, although no synergistic effect with weed control, as has been found in southern pine (Duba et al. 1985, Shiver and Rheney 1992), was observed. The seed orchard source had a greater influence on diameter and volume growth than on height growth during both growing seasons. However, the response in height growth is usually not expected until the third year after outplanting because of the effects of planting shock. In view of decreased proportional differences between seed sources from the first to the second year, one must consider the nursery regime as a potentially major contributor to the observed effects.

Initial Seedling Size

In this study, the relationship between initial seedling size and seedling size after two growing seasons is notable regardless of treatment applied. In other experiments initial seedling size has been positively related to long-term growth of Douglas-fir over a range of site conditions and competition levels (Long and Carrier 1993, Newton et al. 1993). Initial seedling height is related to seedling ability to escape the effects of deer browse and overtopping vegetation. Initial seedling diameter is related to seedling ability to generate root volume, which helps the seedling reach larger volumes of soil, gaining access to soil moisture in the presence of herbaceous vegetation. Size is also related to leaf area, the photosynthetic organ. Long and Carrier (1993) positively associated increasing root mass with seedling survival under environmental stress, and Rose et al. (1991) showed that root volume was a significant factor in the survival and growth of three seed sources of Douglas-fir over 2 growing seasons.

The results of this study indicate that early control of herbaceous competition in conjunction with large planting stock is the silvicultural treatment that most contributes to Douglas-fir growth, through enhancement of resource availability. Seed source selection may or may not have influenced growth, depending on the degree of confounding of nursery influences (unmeasured). Nitrogen fertilization should be approached cautiously in new plantations, as the response may be negligible or negative if it upsets the competitive picture, soil chemistry, or seedling nutrient balance. If used, nitrogen fertilizer should be applied only on deficient sites, and in conjunction with weed control and with other soil amendments as needed to maintain balanced seedling nutrition.

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