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Original article

Interaction of initial seedling diameter, fertilization and weed control on Douglas-fir growth over the first four years after planting

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Abstract – Planting larger stock, fertilization and added years of weed control are often employed to increase growth rate of plantations. We evaluated these techniques using a replicated factorial study design repeated in two diverse locations in western Washington State, USA. Two different sizes of planting stock, fertilizing at planting and in the following year, and two or three years of weed control were tested. No significant interactions among the treatment levels were found with all treatments influencing Douglas-fir growth in an additive manner. Fourth year stem volume gains were greatest from planting larger initial stock: planting seedlings 2 mm larger in basal diameter resulted in fourth-year stem volume gains of 35% and 43%. The fertilization treatments used produced early gains, but they were short lived. The third-year weed-control treatment had no observable effect on fourth-year stem volume or on volume growth in years three or four.

free-to-grow / herbicide / controlled-release fertilizer / nutrition

Résumé – Interaction du diamètre au collet initial des plants, de la fertilisation et du contrôle de la végétation concurrente avec la croissance du Douglas pendant les quatre années suivant la plantation. Pour accélérer la croissance des plantations, on fait souvent appel à des techniques telles que l'emploi de plants plus gros, la fertilisation ou le contrôle de la végétation concurrente pendant plusieurs années. Nous avons évalué ces techniques au moyen de dispositifs factoriels avec répétitions installés dans deux stations de l'ouest de l'État de Washington aux USA. On a testé les options suivantes : deux catégories de plants pour leurs dimensions, fertilisation à la plantation et l'année suivante, et deux ou trois ans de contrôle de la végétation concurrente. Aucune interaction significative entre traitements n'a pu être mise en évidence. Tous les traitements agissant sur la croissance du Douglas le font de manière additive. La quatrième année, les gains de volume des tiges sont les plus élevés avec le matériel végétal initial le plus gros. Avec des plants dont le diamètre au collet est de 2 mm plus élevé, on obtient la quatrième année des gains sur le volume de tige de 35 et 43 %. Les traitements de fertilisation utilisés se sont traduits par des gains au départ, mais de courte durée. Le contrôle de la végétation de la troisième année n'a pas eu d'effet observable sur le volume des tiges de la quatrième année ou sur la croissance en volume des années trois et quatre.

croissance libre / herbicide / épandage contrôlé de fertilisation / nutrition

1. INTRODUCTION

The use of vigorous nursery stocktypes and aggressive early weed control have resulted in nearly universal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedling survival for all practical purposes on productive forest sites within the Pacific Northwest Region. The current issue is how to attain the greatest seedling growth within the first few years after outplanting. This impetus is in part due to regional regulations requiring lands adjacent to planned harvest units within an ownership to have seedlings "free to grow" prior to harvest [24]. Additionally, the potential economic benefit from faster early plantation growth that may result in shortened rotation ages has greatly increased the interest in pushing young plantations to grow as fast as possible.

The traditional silvicultural tools used to enhance early Douglas-fir plantation growth have been planting a target seedling, improved genetics, weed control, and fertilization [30]. A variety of studies have demonstrated that planting stock with larger initial stem diameter can accelerate early plantation survival and growth [11, 22, 41]. Similarly, several studies have demonstrated positive survival and growth responses of Douglas-fir to site preparation and first-year and sometimes second-year herbaceous weed control [6, 16, 20, 28, 42]. The response to early fertilization has been less consistent, with examples of positive, negative, or mixed

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Table I. Results of soil chemical nutrient analysis at the Orting and Belfair sites.

Site Soil horizon	CEC meq/100 g	pH	Total N %	NH_4 mg kg^{-1}	P mg kg^{-1}	K mg kg^{-1}	Ca meq/100 g	Mg meq/100 g	Cu mg kg^{-1}	Fe mg kg^{-1}	Zn mg kg^{-1}	Mn mg kg^{-1}	B mg kg^{-1}
Orting													
A-horizon	16	5.6	0.46	5.6	10	78	1.4	0.4	0.56	45.8	0.88	4	0.4
B-horizon	8.9	5.8	0.23	2.4	9	43	0.3	0.2	0.2	15.6	0.02	0.9	0.2
Belfair													
A-horizon	19.9	5.2	0.32	8	30	74	3.5	0.9	0.86	136	7.66	153	0.5
B-horizon	5.4	5.6	0.08	2	36	31	0.3	0.1	0.54	44.4	0.4	5	0.2

responses reported by a number of investigators [5, 7, 23, 29, 39, 40].

In the Pacific Northwest, the bulk of the studies evaluating reforestation techniques have tended to examine a single silvicultural approach at a time. For example, several studies have examined the impact of different weed control regimes on growth [4, 10, 37, 38], or the impact of various fertilizers [5, 40]. Fewer studies can be found that evaluated the interactive effect of more than one silvicultural treatment, such as the effect of weed control in concert with fertilization [23, 29, 44]. Of those studies that examined how seedling characteristics might impact growth, most were restricted to examining the effects of different stock sizes and types on early growth, although some have included site characteristics as an additional factor [8, 9, 26].

In this paper we present results from two independent studies that used factorial combinations of three of these early silvicultural approaches: stock size, weed control, and fertilization. We evaluated past responses to the above silvicultural treatments and chose those that resulted in the greatest success. We then combined them into a single study to evaluate the interactive effects of different combinations of these approaches.

2. METHODS

2.1. Study areas

Two independent experiments were established in Washington State: one on the western slope of Mount Rainier, east of the town of Orting, and the other on the western coast of the Puget Sound near the town of Belfair. Both sites had been harvested during the summer of 1996; the treatment regimes were established in spring 1997.

Prior to harvest, the Orting site supported a well-stocked, naturally regenerated second-growth stand of Douglas-fir with a small component of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn ex D. Don). The study site is at an elevation of 523 m (1700 ft) and on generally flat ground that allowed for whole-tree skidder yarding. This resulted in little slash and several skidder trails randomly distributed across the site. Soils are in the Zynbar series, which are medial frigid Entic D loam soils averaging 152.4 cm (60 in) in depth. The site receives approximately 172.7 cm (68 in) of rainfall each year with only 10% of this coming during the summer months. Kings 50 year site index is 37.8 m (123 ft). Soil samples of the A and B horizons were collected in the first year of establishment and analyzed for nutrient status. The analysis results are shown in Table I.

Before harvest, the Belfair site consisted of a well-stocked Douglas-fir stand with a minor component of western hemlock, western white pine, and lodgepole pine. The site was located on a flat to undulating slope at an elevation of 400 feet. It was shovel logged with slash piled and left on the site. Soils are derived from a glacial till parent material and are gravely to very gravelly sandy loams. They are moderately well drained and are 58 cm to 102 cm in depth. Precipitation averages 135 cm per year with 94% of the moisture falling in the fall, winter and spring months. Fifty year Kings site index is 32.9 m. Soil nutrient analysis is shown in Table I.

2.2. Design

Each site was considered an independent experiment with both utilizing the same randomized block design. Two levels of weed control, two levels of initial stock sizes, and three levels of fertilization were applied factorially providing twelve separate treatments. There were five blocks at the Belfair site, but only four blocks at the Orting site. Each treatment unit (square plot) within a block consisted of 36 trees planted on a grid spacing of 2.44 m × 2.44 m (8 ft × 8 ft). A row of buffer trees was included to separate contiguous plots and encircled plots on the outside edge of a block. All seedlings were planted in early February 1997 at both sites.

2.3. Vegetation control treatments

Two vegetation control treatments were used: control of all vegetation for two years and control of all vegetation for three years. Vegetation control was accomplished with herbicides, the goal being to maintain operational weed-free conditions as much as possible for either two or three years, depending on the treatment. The herbicides used and rates varied between the two sites due to different target weed communities and expected efficacy of treatment.

The Orting site received a helicopter applied broadcast spray with 210 g/ha of Oust® and 0.73 L/ha of Transline® on April 24th 1997. In Sept. 1997, a directed spray of 2% Accord® in water was applied by backpack sprayer to all hardwoods (cottonwood, alder, elderberry, blackberry) and to western brackenfern (*Pteridium aquilinum* (L.) Kuhn) and western swordfern (*Polystichum munitum* (Kaulf. Presl.) invading the site. A follow-up treatment (a 4% solution of Garlon® in Web Oil®) for the remaining hardwoods was applied in April 1998. No herbaceous control herbicides were applied in year two. In the spring of the third year a broadcast application of 4.67 L/ha Velpar and 140 g/ha Oust® was applied by backpack to the three-year vegetation-control plots.

The Belfair site received a 245 g/ha broadcast treatment of Oust® using backpack sprayers in mid April 1997. The site was treated again in early April 1998 with a 3.5 L/ha Velpar broadcast treatment and a directed application of a 5% solution of Garlon® in Web Oil® on all salal (*Gaultheria shallon* Pursh), Oregon grape (*Mahonia aquifolium* (Pursh) Nutt.) and evergreen huckleberry (*Rubus laciniatus* Willd.) plants within the plot areas. The third-year weed-control treatment consisted of another 3.5 L/ha Velpar application in early April 1999 to the appropriate plots.

2.4. Stem diameter size class treatments

The caliper size-class treatments consisted of a small- and large-diameter classes, sorted at the nursery from seedlings coming from the same beds. The seedlings used were grown at two separate nurseries, the trees for Orting at one and those for Belfair at another. Prior to lifting, representative samples of seedlings were measured at both nurseries. From these data two diameter-sort size ranges were determined, which encompassed 60% of the seedlings grown in the beds, but did not include the extremely small or extremely large seedlings from the population. The large diameter class for the Orting site was 10–12 mm and for Belfair, it was 8–10 mm. The small diameter class at Orting was 6–8 mm, and at Belfair, it was 5–7 mm. Seedlings that were either smaller or larger than the two size groupings were returned to the nursery for planting elsewhere.

2.5. Fertilization treatment

The three fertilizer treatments were a no-fertilizer treatment (NF), fertilization at the time of planting (1F), and an additional fertilization following the first growing season (2F). The 1F treatment was accomplished by placing 70 g of a specially prepared 10–21–6 mix (7 g N; 9.2 g P; 5 g K) of the O.M. Scotts & Sons Co. controlled-release fertilizer in the hole at planting. This fertilizer released nutrients gradually over a six to eight month period. A thin layer of soil was placed between the roots of the planted seedlings and the fertilizer in the bottom of the planting hole to prevent root burn. The 2F treatment used the same 70 g of the 10–21–6 mix, which was dibbled into a slit 12 cm (5 in) in depth, as close to the main stem as possible without causing damage to the seedling, generally 10 to 15 cm. This treatment was applied in December after the first growing season.

2.6. Measurements

2.6.1. Seedlings

In March of 1997 height and basal diameter (10 cm above groundline) all the seedlings in the plots were measured. At this time mortality was also recorded. Seedlings were again measured for height and basal diameter in the fall after height growth had ceased for each of the next four years. From these measures, stem volume was calculated using the formula for a cone, in cm^3:

$$\text{volume} = \frac{\pi \times (\text{diameter}^2) \times \text{height}}{12}. \quad (1)$$

2.6.2. Foliage nutrients

Foliage samples were collected from eight randomly selected seedlings in each plot after the first and second year of growth. The samples were collected in fall from lateral branches in the upper third of the crown and consisted of only the current year's growth. The needles were removed from the samples and pooled together by plot. Dry weight of a random 100 needles were determined for each plot and the samples were dried, ground, and sent to a lab for analysis of the concentrations of all major and micro nutrients with standard laboratory procedures.

2.6.3. Vegetation

The percent cover of vegetation in a 1-m radius plot around each seedling at both sites was visually estimated in all four years of the study. These estimates were performed in mid-July, when the greatest level of vegetation cover was expected to occur on the sites. The most predominant species were recorded in each plot, as was a modal height of the vegetation in the plot.

2.7. Analysis

Analysis of variance was used to compare differences in fourth-year stem volume and percent mortality at each study site independently. Additional ANOVA analyses were performed on yearly stem diameter growth, height growth, stem volume growth, vegetation cover, and vegetation height by year, independently by site. Residuals of all analyses were examined for lack of normality and equal variance, and required no transformations. All analyses were performed with the factorial treatment structure such that interactive effects among treatment could be examined. Means were compared using Fishers least significant difference tests. In cases when no significant interactions between main treatment factors were found means for a treatment factor were pooled across the other two factors for this test.

Foliar nutrient concentrations and needle weights were analyzed with ANOVA using the first and second years. Orthogonal contrasts (shown below) were used to compare differences between the stock size treatments, vegetation control treatments, and the fertilization treatments for all the major and minor nutrients.

Orthogonal contrasts examined:

- Large vs. small diameter sort,
- 2 years weed control vs. 3 years weed control,
- NF vs. fertilization,
- 1F vs. 2F treatment.

3. RESULTS

Results were remarkably similar between the two different sites, given the differences in soils and locations. No consistent interactions were found among any of the treatment factors. For both sites the p values for all interactions ranged from 0.0783 to 0.9204. The V × F p value was 0.0783 for height. The next closest was 0.19 (S × V × F) for diameter, but all other p values were 0.27 and above for all responses. This suggests that the response to treatments was additive in nature. For example, the benefit derived from planting larger stock was similar regardless of fertilizer or weed control treatment and vice versa. This allows for results of each treatment factor to be presented independently of the others. Treatment responses varied by site and are presented separately.

3.1. Orting

3.1.1. Seedling mortality

First-year seedling mortality averaged less than 2% for all treatments. Mortality increased through year four and by initial

Table II. Mean fourth-year diameter, height, stem volume, and mortality by treatment factor for each year of the study and by site.

Parameter/treatment	Size		Fertilization			Vegetation control	
	Small	Large	NF	1F	2F	2-years	3-years
Orting Site							
Diameter (mm)	34.6a[1]	39.0b	36.0a	37.4a	37.1a	35.2a	38.4b
Height (cm)	196.7a	223.2b	205.6a	213.8a	210.5a	212.6a	207.3a
Stem volume (cc)	775.2a	1043.2b	826.4a	961.2a	939.9a	832.8a	985.5b
Mortality (%)	8.9a	5.2b	3.8a	6.3a	11.1b	6.3a	7.9a
Belfair Site							
Diameter (mm)	34.2a	39.0b	34.8a	37.2b	37.7b	36.0a	37.1a
Height (cm)	176.7a	198.6b	178.5a	188.4b	196.1b	186.3a	189.0a
Stem volume (cc)	619.7a	891.1b	651.1a	791.4b	823.7b	725.2a	785.6a
Mortality (%)	7.6a	6.6a	4.2a	7.9ab	9.2b	6.3a	7.9a

[1] Values in each row within a treatment factor (size, fertilization, vegetation control) that are followed by the same letter are not significantly different ($p \leq 0.05$). Means were compared using the Fisher protected means comparison test. Means for a given treatment factor (size, fertilization, vegetation control) are pooled across the other two factors.

size class ($p = 0.0117$) and fertilization treatment ($p < 0.0001$), but not by weed control treatment ($p = 0.5949$). There was little difference in first-year mortality between the two size classes, but this difference increased with time. By year four, mortality had increased to 5.2% for the large seedlings and 8.9% for the small seedlings (Tab. II).

Mortality increased with the 1F treatment only slightly in year one, but mortality increased with time. By year four, the greatest level of mortality occurred in the 2F treatment (11.1%), the 1F treatment had a mean mortality of 6.3%, while the NF treatment had 3.8% mortality rate.

3.1.2. Seedling growth

The difference in stem volume between the two diameter size classes increased greatly from 4.5 cm^3 at planting to 268 cm^3 by year four (Tab. II). The larger size class had significantly greater stem volume growth in all four years of the study. However, the percentage gain in stem volume due to planting larger stock decreased each year of the study. In year one, stem volume was 92% greater in the larger size class treatment than in the smaller, which decreased to a 35% gain by year four.

At planting, there was a 2.1-mm difference in basal diameter and a 13-cm difference in height between the larger and smaller size classes. By year four these differences increased to 4.4 mm and 26.5 cm, respectively. No differences in height were found in year one or for diameter growth in years one or two among size class treatments (Tab. III). In year three, stem diameter growth was greater for the larger size (10.1 cm) than for the small size class (9.1 cm). In year four, this difference continued to increase, with the larger size class growing 12.3 cm and the smaller class growing 10.8 cm. Similar increases occurred with height growth in years two through four.

The 1F treatment increased fourth-year stem volume by 140 cm^3 over the NF treatment (Tab. II). No differences in fourth-year stem volume between the 1F and 2F treatments were observed. Fertilization resulted in a yearly increase in stem volume growth for the first three years, but differences could no longer be identified by year four (Tab. III). The percentage of stem volume gain due to fertilization decreased more over time than did the gains from planting larger initial stock. Fertilization resulted in a 61% gain (data not shown) in stem volume after the first year, but this had dropped to non-significant ($p = 0.87$) 16% by the fourth year (826.4 vs. 961.2).

Differences in diameter growth by fertilizer treatment were found only in year one, with fertilization increasing diameter growth by 3.35 mm (Tab. III). Yearly height growth was greater in the 1F treatments in year one. No differences in height growth by fertilization treatment were observed in year two. The 2F treatment resulted in greater height growth than either other treatment in year three, but did not differ in year four.

The third-year weed control treatment increased third-year stem volume an additional 153 cm^3, a 12% gain (data not shown). This increased to an 18% gain by year four (Tab. II). The weed control treatment increased stem diameter growth in year three, which continued to increase into year four (Tab. III). However, height growth was not impacted in either year.

3.1.3. Vegetation

Vegetation cover percentage and height did not vary significantly by fertilizer treatment or initial stock size in any year of the study, or by weed control treatment in years one and two (Tab. IV). Vegetation cover averaged 26% with an average height of 25.9 cm across all treatments in year one. Cover and height increased to 50% and 50 cm in year two. The third-year vegetation control treatment significantly reduced cover percentage from 75% in the 2-year treatment to 47% cover in the three-year treatment. Vegetation height also differed, being 81 cm in the two-year treatment and 73 cm in the three-year treatment.

Table III. Mean diameter, height, and stem volume growth by treatment factor for each year of the study and by site.

Year/treatment	Size		Fertilization			Vegetation control	
	Small	Large	NF	1F	2F	2-years	3-years
Orting site							
Diameter (mm)							
Year one	3.0a[1]	3.1a	1.8a	3.7b	3.6b	3.0a	3.0a
Year two	6.4a	6.5a	6.6a	6.4a	6.3a	6.5a	6.4a
Year three	9.1a	10.1b	9.6a	9.5a	9.7a	8.8a	10.4b
Year four	10.8a	12.3b	11.8a	11.6a	11.3a	10.8a	12.3b
Height (cm)							
Year one	13.2a	11.9a	10.0a	15.0c	12.7b	12.4a	12.7a
Year two	39.6a	42.0b	43.0a	39.2a	40.2a	40.1a	41.5a
Year three	48.0a	52.9b	47.5a	52.0b	51.9b	50.5a	50.4a
Year four	55.7a	64.9b	60.0a	61.0a	59.85a	58.6a	62.0a
Stem volume (cc)							
Year one	7.3a	11.6b	5.1a	12.4b	10.9b	9.4a	9.6a
Year two	51.3a	68.5b	52.2a	63.6b	63.9b	60.0a	59.8a
Year three	188.6a	256.1b	195.1a	233.3b	238.5b	205.1a	239.5a
Year four	520.9a	699.2b	565.3a	645.5a	619.3a	549.7a	670.4b
Belfair site							
Diameter (mm)							
Year one	4.0a	4.22a	1.9a	5.4b	5.1b	4.0a	4.3a
Year two	7.3a	7.87a	7.6ab	7.1a	8.1b	7.5a	7.7a
Year three	10.2a	11.1a	10.8a	10.6a	10.7a	10.0a	11.3b
Year four	8.1a	8.9a	8.7a	8.7a	8.1a	8.8a	8.2a
Height (cm)							
Year one	9.3a	10.7b	6.7a	11.5b	11.8b	10.2a	9.8a
Year two	33.6a	31.8a	31.2a	31.7a	35.3b	32.7a	32.7a
Year three	42.7a	48.3b	44.3a	45.5a	46.7a	46.7a	44.3a
Year four	54.0a	60.9b	54.5a	58.4a	59.3a	54.7a	60.3b
Stem volume (cc)							
Year one	9.0a	13.9b	4.3a	15.2b	14.7b	11.1a	11.8a
Year two	50.3a	73.8b	46.9a	63.4b	75.9c	60.4a	63.7a
Year three	189.2a	269.4b	194.8a	232.5ab	260.5b	215.3a	243.2a
Year four	368.8a	528.1b	400.4a	481.5a	463.5a	435.2a	461.7a

[1] Values in each row within a treatment factor (size, fertilization, vegetation control) that are followed by the same letter are not significantly different ($p \leq 0.05$). Means were compared using the Fisher protected means comparison test. Means for a given treatment factor (size, fertilization, vegetation control) are pooled across the other two factors.

Differences in cover and height were still present into year four with the two-year treatment having greater cover (68%) than the three-year treatment (56%). Vegetation height showed the opposite response, with the tallest vegetation found in the three-year treatment vs. the two-year treatment (121 cm and 92 cm, respectively).

The most predominant competitive species across the site changed through the four years of the study and after year three, the predominant species varied by vegetation control treatment. In year one, brackenfern, bedstraw (*Galium aparine* L.), and swordfern were the most predominant species (Tab. IV). In year two the site was largely dominated by herbaceous species including woodland goundsel (*Senecio sylvaticus* L.), false dandelion (*Hypochaeris radicata* L.), and fireweed (*Epilobium angustifolium* L.). By year three, false dandelion was the most predominant species in the two-year

Table IV. Mean vegetation cover and height in each year of the study at both experimental sites by vegetation-control treatment. Mean frequency of the dominant species on a per-plot basis by vegetation-control treatment.

Site	Year-1	Year-2	Year-3	Year-4
Orting 2-year vegetation-control treatment				
Vegetation cover (%)	26.3	48.6	75	68.4
Vegetation height (cm)	24.6	50.4	81.3	92.3
Mean frequency species was the dominant cover in a plot				
Hypochaeris radicata	2.3	10.1	38.8	37.2
Epilobium angustifolium	6.4	13.3	29.2	29.6
Pteridium aquifolium	12	3.7	4.4	10.5
Sambucus racemosa	7.4	6.5	4.5	9.8
Polysticum munitum	15.4	3.7	0.6	2.1
Galium aparine	16.7	4.6	0	0
Dicentra formosa	8.3	2.3	0	0
Senicio sylvaticus				
No cover	7	4.5	6.3	0.7
Orting 3-year vegetation-control treatment				
Vegetation cover (%)	25.6	51.1	46.7	56
Vegetation height (cm)	27.2	51.3	73.3	121
Mean frequency species was the dominant cover in a plot				
Hypochaeris radicata	1.3	9.1	6.1	6.6
Epilobium angustifolium	10.6	17.8	54.9	52.1
Pteridium aqualinum	15.5	4.1	5.1	7.9
Sambucus racemosa	8.5	6.3	17.2	20.7
Polystichum munitum	14.1	1	0	0.1
Galium aparine	17.9	5.3	0.2	0
Dicentra formosa	2.3	1.4	0	0
Senicio sylvaticus	0.7	21.1	0	0
No cover	4.3	0	5.7	2.3
Belfair 2-year vegetation-control treatment				
Vegetation cover (%)	8.3	25.3	53.7	39.9
Vegetation height (cm)	16.8	39.4	67.8	57.3
Mean frequency species was the dominant cover in a plot				
Pteriduim aquifolium	21.3	66	68	73
Galtheria shallon	44.8	13.7	8.6	6.3
Vacinium ovatum	12.2	1.4	0.5	0.46
Epliobium angustifolium	0.37	3.6	5.1	4.8
Senecio sylvaticus	0.01	0.7	5.6	0.01
Rubus ursinus	1.2	0.7	0.9	0.4
No cover	15.7	9.1	6.2	2.3

Table IV. Continued.

Belfair 3-year vegetation-control treatment				
Vegetation cover (%)	8	24	39	39.6
Vegetation height (cm)	16.8	37.1	51.4	59.6
Mean frequency species was the dominant cover in a plot				
Pteriduim aquifolium	18	55	54	60
Galtheria shallon	43	16.8	18.6	11
Vaccinium ovatum	17	8.7	1.2	1.8
Epliobium angustifolium	0.5	8.5	11.3	12.4
Senecio sylvaticus	0.4	0.9	0.4	0.4
Rubus ursinus	1.6	1.9	0.5	0.3
No cover	14.8	8.7	8.3	3.5
ANOVA contrast "2-year vs. 3 year"	*p*-value	*p*-value	*p*-value	*p*-value
Orting				
Vegetation cover percentage	0.805	0.481	0.0001	0.0001
Vegetation height	0.175	0.797	0.031	0.0001
Belfair				
Vegetation cover percentage	0.836	0.631	0.0001	0.881
Vegetation height	0.991	0.493	0.168	0.532

vegetation control treatment and stayed the dominant into year four. The three-year vegetation control treatment greatly reduced the dominance of false dandelion and increased the importance of fireweed and elderberry (*Sambucus racemosa* L.), a trend that continued into year four.

3.1.4. Needle nutrients

Nutrients were measured during years one and two prior to the third-year weed control treatment. For this reason, differences due to weed control would not be expected and were not found for any nutrient sampled. No differences in nutrient concentration between the seedling size classes occurred in either year one or two (Tab. V). The fertilization treatments resulted in an increase in first-year N and B concentrations and decreases in P and K concentrations. No other nutrient concentration varied by fertilizer treatment in year one.

Foliage concentrations of N, P, K, Ca, S, Mg, and B dropped considerably from year one to two regardless of treatment (Tab. V). Most notable among these was N, which dropped from a first-year range of 1.85%–2.07% to 1.42%–1.52% in the second year. Concentrations of the remainder of nutrients tended to either stay the same or increase. Needle weight in year two was less in the fertilized treatments than in the NF treatments, but did not differ between the 1F and 2F treatments. Boron and Fe concentrations were greater in the fertilized treatments, while Ca was less. Among fertilized treatments, B concentration was greater in 2F treatment than the 1F treatment. Concentration of K was greater in the 1F treatment than the 2F, but neither differed from the NF treatment.

Table V. Means of foliar nutrient concentrations for the Orting site by fertilizer treatment, and caliper size-class treatments. Results of statistical contrasts from the ANOVA procedure. Values in bold are significant at $p < 0.05$.

Year 1	Needle weight	N %	P %	K %	Ca %	S %	Mg %	Cu mg kg^{-1}	Fe mg kg^{-1}	Zn mg kg^{-1}	Mn mg kg^{-1}	B mg kg^{-1}
Fertilization treatment												
No fertilizer	0.3531	1.82	0.1951	0.7155	0.371	0.1682	0.1004	3.4	47.2	27.3	330	30.96
1-year fertilizer	0.3681	2.01	0.1801	0.6365	0.345	0.1659	0.098	3.16	42.9	26.1	320	50.02
2-years fertilizer	0.4	2.07	0.156	0.6094	0.344	0.1671	0.104	3	42.6	23.1	276	57.2
Caliper size-class treatment												
Small	0.3946	1.99	0.18	0.6689	0.3729	0.172	0.1005	3.32	45.4	28.1	329	46.2
Large	0.3529	1.94	0.17	0.6386	0.3341	0.1622	0.1015	3.05	43	22.9	289	45.9
Contrast “large vs. small”	0.0648	0.46	0.3675	0.2008	0.0528	0.1967	0.7878	0.1247	0.3106	0.006	0.0572	0.9359
Contrast “no fertilizer vs. fertilizer”	0.1888	**0.0016**	**0.0002**	**0.0007**	0.213	0.837	0.8305	0.088	0.0831	0.1602	0.1433	**0.0001**
Contrast “1 year vs. 2 years”	0.2398	0.4516	**0.0032**	0.3475	0.9742	0.893	0.2863	0.4469	0.9152	0.1799	0.0834	0.1517
Year 2												
Fertilization treatment												
No fertilizer	1.17	1.42	0.1306	0.525	0.35	0.1319	0.0912	7.31	76.3	32.2	332	14.61
1-year fertilizer	0.98	1.46	0.1419	0.5688	0.304	0.1344	0.085	7.25	88.9	32.1	422	18.6
2-years fertilizer	0.97	1.52	0.1425	0.5188	0.299	0.1325	0.086	7.37	85.6	30.9	441	21.6
Caliper size-class treatment												
Small	1.018	1.47	0.138	0.5458	0.3354	0.1325	0.0879	7.25	82.2	34.5	441	18.38
Large	1.067	1.47	0.139	0.5292	0.3	0.1333	0.087	7.38	85	28.9	343	18.15
Contrast “large vs. small”	0.1565	0.9422	0.916	0.2959	0.0649	0.8102	0.8293	0.6333	0.3708	0.012	0.0518	0.8408
Contrast “no fertilizer vs. fertilizer”	**0.0001**	0.0979	0.1735	0.268	**0.0192**	0.6714	0.1759	1.0	**0.002**	0.7526	0.0944	**0.0001**
Contrast “1 year vs. 2 years”	0.7291	0.2638	0.9485	**0.0138**	0.8485	0.6594	0.7917	0.6967	0.3769	0.6523	0.9843	**0.0428**

3.2. Belfair

3.2.1. Seedling mortality

Seedling mortality averaged less than 5% for all treatments after one growing season. Mortality increased slightly over the first four years, but by year four it still averaged less than 10% across all the study factor levels (Tab. II). Of the three factors evaluated (initial stock size, vegetation control, and fertilization), only the fertilization treatment had a significant impact on seedling mortality ($p = 0.05$). Plots that were fertilized had 2% more mortality than unfertilized plots after the first year. By year four, this had increased to a 4%–5% difference. No statistical differences were found between the 1F and 2F fertilization treatments.

3.2.2. Seedling growth

Similar to the Orting site, the difference in stem volume between the two size classes increased from planting through year four, from 3.6 cm^3 (data not shown) to 272 cm^3 (Tab. II). The larger size class had significantly greater stem volume growth in all four years of the study (Tab. III). Like Orting, the percentage gain in stem volume from planting larger stock dropped each year of the study. At planting, the larger size class seedlings had stem volumes 164% greater than the small class. By year four, this percentage difference had dropped, with the larger size class now 43% greater than the smaller (619.7 vs. 891.1).

At planting there was a 2.2-mm difference in basal diameter and a 9-cm difference in height between the larger and smaller size classes. These differences increased to 4.8 mm and 21.9 cm, respectively, by year four (Tab. II). However, differences in stem diameter growth were not significant in any one year (Tab. III). Height growth was greater for the larger size class every year except year two.

The 1F treatment resulted in an increase in fourth-year volume of 140 cm^3 over the NF treatment, while the 1F and 2F treatment did not differ (Tab. III). Differences in volume growth were observed between the NF and 1F treatment each year of the study except year four. The 2F treatment had greater volume growth than both the NF and 1F treatment in year two. The 2F treatment also had greater volume growth than the NF treatment in year three but did not differ in year four. The 1F treatment resulted in 125% (data not shown) increase in volume in year one, which decreased to a gain of 22% by year four (651.1 vs. 791.4).

Table VI. Means of foliar nutrient concentrations for the Belfair site by fertilizer treatment, and caliper size class treatments. Results of statistical contrasts from the ANOVA procedure. Values in bold are significant at $p < 0.05$.

Year 1	Needle weight	N %	P %	K %	Ca %	S %	Mg %	Cu mg kg^{-1}	Fe mg kg^{-1}	Zn mg kg^{-1}	Mn mg kg^{-1}	B mg kg^{-1}
Fertilization treatment												
No fertilizer	0.36	2.05	0.285	0.615	0.373	0.164	0.099	3.33	46.3	38.8	457	16.3
1-year fertilizer	0.47	2.66	0.18	0.528	0.379	0.178	0.093	2.55	40.82	19.5	330	45.7
2-years fertilizer	0.43	2.62	0.173	0.519	0.407	0.177	0.098	2.38	38.65	15.9	298	45.7
Caliper size-class treatment												
Small	0.431	2.475	0.216	0.565	0.409	0.183	0.089	2.76	40	27.57	402	35.4
Large	0.406	2.2	0.209	0.543	0.364	0.165	0.104	2.73	43.34	21.88	321	36.5
Contrast "large vs. small"	0.1577	0.353	0.387	0.0918	**0.0038**	**0.0003**	**0.0004**	0.7316	0.0855	**0.0014**	**0.0246**	0.8146
Contrast "no fertilizer vs. fertilizer"	**0.0001**	**0.0001**	**0.0001**	**0.0001**	0.2207	**0.0046**	0.318	**0.0001**	**0.0011**	**0.0001**	**0.0004**	**0.0001**
Contrast "1 year vs. 2 years"	**0.0489**	0.6108	0.4777	0.5896	0.1318	0.8446	0.283	0.2227	0.5585	0.089	0.4508	0.9945
Year 2												
Fertilization treatment												
No fertilizer	1.05	1.49	0.1855	0.5	0.355	0.1295	0.1025	8.25	143.45	34.45	366.8	7.97
1-year fertilizer	0.915	1.39	0.1645	0.475	0.308	0.1235	0.095	7.9	162.85	29.6	425.95	9.6
2-years fertilizer	0.972	1.5	0.1365	0.47	0.308	0.112	0.0945	7.4	162.1	28.45	501.8	16.2
Caliper size-class treatment												
Small	0.945	1.48	0.163	0.4767	0.3287	0.122	0.096	7.93	153.93	32.7	448.9	10.93
Large	1.0163	1.44	0.158	0.4867	0.314	0.1213	0.099	7.76	158.33	28.9	414.2	11.57
Contrast "large vs. small"	0.182	0.6098	0.2541	0.5927	0.2616	0.9074	0.3769	0.5474	0.6919	**0.0266**	0.3238	0.6696
Contrast "no fertilizer vs. fertilizer"	0.055	0.481	**0.0001**	0.1694	**0.0006**	0.0584	0.0567	**0.0455**	0.1111	**0.0031**	**0.0117**	**0.003**
Contrast "1 year vs. 2 years"	0.3811	0.1039	**0.0028**	0.8269	0.6598	0.1064	0.9134	0.1446	0.956	0.5537	0.0815	**0.0007**

Diameter growth was greater in the 1F treatment (5.4 mm) than in the NF treatment (1.9 mm) in year one (Tab. III). In year two, the 2F treatment had greater diameter growth than the 1F, but not the NF treatments, which did not differ. No differences in diameter growth were observed in years three or four. A similar pattern of yearly growth response was observed for height.

The third-year weed-control treatment had no observable effect on fourth-year stem volume or on volume growth in years three or four. The weed-control treatment increased third-year diameter growth slightly (1.3 mm), but no increases in third-year height growth were found. However, a 5.6 cm gain in height was observed in year four.

3.2.3. Vegetation

Vegetation cover percentage and height did not vary significantly by fertilizer treatment or diameter size class in any year of the study, or by vegetation control treatment in years one and two. Vegetation cover averaged 8.17% across all treatments in year one. Cover increased to 24.6% in year two and did not differ by any of the treatment factors (Tab. IV). The three-year weed control treatment significantly reduced cover percentage from 53.6% in the two-year treatment to 39.0% cover in the three-year treatment. Vegetation height was reduced from 68 cm in the two-year to 51 cm in the three-year vegetation-control treatment. By year four, no differences in cover or height were observed between the vegetation control treatments; cover and height averaged 40% and 58 cm, respectively, across all treatments.

The most predominant species in all four years of the study were salal, bracken fern, evergreen huckleberry, fireweed, and trailing blackberry (*Rubus ursinus* Cham. & Schlecht.) (Tab. IV). Bracken fern was by far the most frequent competitor on the site in all but the first year. The three-year vegetation control treatment tended to slightly increase the predominance of fireweed and salal, compared with the two-year vegetation control treatment.

3.2.4. Nutrients

In year one, differences in nutrient concentrations between the size class treatments existed for Ca, S, Mg, Zn, and Mn (Tab. VI). Of these, concentrations were lower in the large stock size compared with the smaller size for all but Mg. The 1F treatments impacted nutrient concentrations of all nutrients sampled except Ca and Mg. Fertilization resulted in an increase of N, S, and B and a decrease in concentration of P, K, Cu, Fe, Zn, and Mn. Fertilization also increased needle weight in year one.

Foliage concentrations of N, P, K, Ca, S, and B dropped considerably in year two from levels measured in year one, regardless of treatment (Tab. VI). Most notable among these changes was N, which dropped from a first year range of 2.05% to 2.62%, down to 1.39% to 1.5% in year two. Boron also dropped from a high of 45.7 ppm in the fertilized treatments in year one to a high of 16.2 ppm in year two. Concentrations of the remainder of nutrients tended to either stay the same or increase, with some – such as Cu and Fe – doubling or tripling in concentration in measurement year two. Zinc concentrations continued to be less in the smaller caliper size class than in the larger size class in year two, although this difference was small. The fertilizer treatments resulted in an increase in foliar concentrations of B and Mn and a decrease in P, Ca, Cu, and Zn, compared with the NF treatment. Differences between the 1F and 2F treatments were found for only B and P. Boron concentration was increased, while P decreased. Needle weights were marginally ($p = 0.055$) affected by the 2F treatment, with needle weight tending to be smaller in the fertilized than in the NF treatments.

4. DISCUSSION

4.1. Interaction of treatments

South et al. [34] proposed several potential interactive response patterns among nursery and site-preparation treatments. Among these was a non-interactive or additive response. Our results mirrored this additive response pattern, with no treatment interacting with any other. In other words, gains from planting larger stock were additive to gains from fertilizing or applying an additional third year of weed control. However, there were large differences in the magnitude of response to different treatments.

There are few examples in the reforestation literature that evaluate the interactive effects of planting different sized seedlings and either weed control or fertilization for conifers. Only one study was found that evaluated the interaction of all three factors: stock size, fertilization, and weed control [33]. This showed that gains in mid-rotation (12-year) loblolly pine resulting from planting larger stock were additive to those from either fertilization or weed control. However, in their study, fertilization and weed control interacted such that without weed control there were no fertilizer responses. In studies wherein the interactions between seedling size at planting and weed control were examined, the responses have been additive [13, 17, 31, 32]. We are aware of only two published reports that compare planting different sized Douglas-fir seedlings that received similar nursery cultural histories in combination with fertilization treatments. Strothmann [35] found that three-year height growth gains were additive to those from fertilization with Agriform® tablets on a granitic soil in northern California. Rose et al. [25] found no response to fertilization with Agriform fertilizer pellets regardless of seedling size at planting.

The interactive effects of weed control and fertilization on Douglas-fir growth tend to be less consistent than with initial stock size. Our results support those of Rose and Ketchum [23], who reported additive responses to weed control and fertilization at those sites where a fertilizer response was found. This was in contrast to Roth and Newton [29], who found that broadcast urea fertilization resulted in a decrease in survival and growth if no weed control was applied, and no positive responses to fertilization in the presence of weed control. Their results closely mirrored those of White and Newton [44], with a negative response to fertilization in the absence of weed control. It should be noted that in both of the latter two studies, broadcast applications of fertilizer were used. In contrast, Austin and Strand [2] reported a positive growth response to urea-formaldehyde and triple-super phosphate fertilization only when weed control was applied; they added fertilizer to the hole at planting. Similar interactive effects have been identified in other forest environments [12, 33, 36, 39].

Several factors play a role in generating a positive response to early fertilization, including placement, rate, and formulation [3]. The environment of the plantation site must also have adequate growing season soil moisture [15]. This is illustrated nicely by a study that evaluated ponderosa pine growth to weed control and fertilization treatments [21]. They found their best fertilizer responses on moist sites. On drier sites, seedling responses to fertilizers were less relative to weed control and *only* occurred if weed control was applied. It is likely the two years of weed control applied in our study provided an environment favorable to an additive fertilizer and weed control response.

In Sweden Nilsson and Orlander [18] studied the response of newly planted Norway spruce seedlings to fertilization, irrigation and herbicide treatments. Their results showed that stem volume was positively affected by herbicide treatment (H) and by fertilization in combination with herbicide treatment (FH), whereas seedling growth was not affected by fertilization only. By the end of the third growing season the stem volume (cm^3) for the fertilization and herbicide combination was 106.8 versus 29.2 for the control. The FH treatment proved to be a 365% improvement!

4.2. Seedling size response

Planting seedlings 2 mm larger had a greater impact on fourth-year stem volume than either early fertilization or a third year of weed control. The 2 mm difference in stem diameter at planting resulted in a 35% (775.2 vs. 1043.2) increase in fourth-year stem volume at the Orting site and a 43% (619.7 vs. 891.1) increase at the Belfair site. The benefit derived from planting larger stock was consistent with other published studies for Douglas-fir [11, 27, 35]. Similar trends have also been reported for other conifer species in dramatically different environments [17, 31–33].

The duration over time in which differences in initial stem diameter will still be identifiable is unknown. Results from other authors suggest that planting larger stock will produce measurable differences for several years to come [27]. Rose et al. [27] was still able to identify significant differences in stem volume eight years after planting seedlings with larger root volumes. Although root volume was the grading criterion in their study, stem diameter was also larger in the largest root volume class [27]. Differences due to using loblolly pine seedlings only 1 mm larger at planting were still identifiable 12 years later [33].

4.3. Third year weed control response

The third-year weed control treatment had an effect at the Orting site, but not the Belfair site. The lack of response at Belfair is largely attributed to poor efficacy of the third-year herbicide treatment. The predominant competitive species at Belfair (bracken fern, salal, and evergreen huckleberry) proved to be resistant to the Velpar-Oust mixture applied. Both of these herbicides tend to be more effective on germinating forbs and grasses, of which there were few at Belfair. In contrast, the Orting site was rich in grasses and forbs early in the season and the third-year weed control treatment provided a weed-free window that elicited a positive tree growth response. However, by mid-July, when the vegetation surveys were performed, cover was not greatly different between the weed-control treatments. This was due to an expansion of fireweed and elderberry cover. Neither species was much affected by the herbicide treatment, but instead were released from competition similar to the Douglas-fir. Regardless, the third-year weed control treatment resulted in an 18% increase (832.8 vs. 985.5) in stem volume at year four, roughly half that achieved with planting larger stock.

Weed control over the first few years of plantation establishment will result in marked increases in seedling growth [14, 28]. The impact of first-year weed control relative to second- or third-year weed control treatments on Douglas-fir is less understood. Fifth-year Douglas-fir stem volume was increased by 82%, 115%, and 217% for one, two and three years of weed control in the central coast range of Oregon [16]. We are unaware of any other studies in which similar treatment regimes for Douglas-fir were examined, with the exception of O'Dea [19]; in that study, deer browse confounding made it difficult to draw conclusions. Wagner et al. [43] demonstrated differences in conifer response to multiple years of weed control. They found that white pine responds to each additional year of weed control, up to five years, in a near-linear fashion, while Jack and red pine no longer responded after the first two years, and black spruce stopped responding after three years. Our results suggest that on sites where herbaceous species are still present into year three, weed control can continue to elicit a growth response. The ultimate long-term benefit of a third year of weed control has not yet been determined.

4.4. Fertilization response

Early gains from fertilization could no longer be identified at the Orting site in year four and the difference between fertilized and NF treatments at Belfair had decreased. These results support those of Rose and Ketchum [23], who found that initial gains from IBDU (isobutylidene diurea) fertilization was largely restricted to the first two years of growth. Our results contrast with others who have reported an increasing response to fertilization over the first three to seven years of growth [5, 40]. Fertilization resulted in roughly a 2-mm gain in stem diameter in year one at Orting. This gain was easily identified as significant in the first couple years of the study. However by year four, variability in stem diameter increased due to several other microsite factors, and even though a 2-mm gain was still evident in the means of the fertilized and NF seedlings, statistical differences were no longer identifiable. At Belfair, the gain was slightly larger and was still significant into year four, but may not be identifiable in future years, as the trees continue to get larger.

The second-year fertilizer treatment was marginally effective at only one of the two sites. This treatment was dibbled to the side of the seedling, which may explain its lack of effectiveness. Dibbling fertilizer only provides added nutrition to a portion of the rooting zone of a seedling. If no roots are located within this zone the potential to have a positive effect is limited. Others have also demonstrated that dibbled fertilization is less effective at eliciting a growth response than is adding fertilizer to the hole at planting [4, 5].

Foliage nutrient concentrations suggest that most of the gains from fertilization resulted from increasing the availability of N over most other nutrients. Concentrations of P and K dropped, suggesting that both were diluted by the enhanced N-induced growth. Another controlled-release fertilizer, manufactured by J.R. Simplot & Co. and incorporating a different coating, releases P and K at much slower rates than N [1]. Although the coatings are different both the Simplot and Scott's products rely on osmotic diffusion to deliver nutrients. The rate of P and K release from the Scott's controlled release prills may also not be as fast as for nitrogen, although this has not been tested directly. If this is the case, it might be possible to enhance early growth gains by using slightly different fertilizer blends and release technologies.

5. CONCLUSION

Reforestation managers in the Coastal zone of the Pacific Northwest commonly plant a seedling with a basal caliper ranging from 4 to 6 mm and apply one to two years of herbaceous weed control. Our results suggest that the best option for increasing early growth is to plant larger diameter seedlings. Although the fertilization treatments we used produced early gains, they were short lived. Further research is needed to better understand the fate and amount of fertilizers in the forest environment (i.e., nutrient leaching, P fixation, uptake by weeds, insoluble compounds) along with understanding how fertilizers may be applied in ways that produce greater long-term gains. The third-year weed control treatments produced modest gains in stem volume at the Orting site where herbaceous competition was present. The success of third-year weed-control treatments generally will depend on the presence of weed competition and the site-specific effectiveness of the herbicides used.

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