Interaction of vegetation control and fertilization on conifer species across the Pacific Northwest[1]

Robin Rose and J. Scott Ketchum

Abstract: An experiment evaluating three levels of vegetation competition control (no control, 1.5 m^2 of vegetation control, and 3.3 m^2 of vegetation control), each with two fertilization treatments (fertilization at the time of planting with complete slow-release fertilizer (Woodace® IBDU), or no fertilization), was installed at five sites. Two of these sites were planted with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the Oregon Coast Range, one with ponderosa pine (*Pinus ponderosa* Dougl. ex P. Laws. & C. Laws.) in eastern Washington, one with western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in the coastal hemlock zone in Oregon, and one with coastal redwood (*Sequoia sempervirens* (D. Don) Endl.) in northern California. At four of the five sites, mean stem volume, basal diameter, and height of seedlings increased significantly with increasing area of weed control, and the magnitude of difference between treatments increased with time. Fertilization significantly increased seedling size only at the two sites with adequate soil moisture; increases were marginally significant at a third. Response to fertilization was less than from weed control and impacted growth for only the first year, whereas the influence of weed control continued to influence growth the entire length of the study (4 years). Area of vegetation control and fertilization did not interact significantly at any site.

Résumé : Une expérience destinée à évaluer trois intensités de maîtrise de la végétation compétitrice (aucun traitement et traitements de 1,5 et de 3,3 m^2) combinées à deux traitements de fertilisation (fertilisation au moment de la plantation avec un fertilisant complet à action lente (Woodace® IBDU) ou aucune fertilisation) a été installée à cinq endroits. Deux des sites ont été plantés avec des douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) dans la chaîne côtière de l'Oregon, un avec des pins ponderosa (*Pinus ponderosa* Dougl. ex P. Laws. & C. Laws.) dans l'est de l'état de Washington, un avec des pruches de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.) dans la zone côtière de la pruche en Oregon et un avec le séquoia côtier (*Sequoia sempervirens* (D. Don) Endl.) dans le nord de la Californie. Dans quatre des cinq sites, le volume moyen de la tige, le diamètre à la base et la hauteur des semis ont significativement augmenté avec l'augmentation de l'intensité de la maîtrise de la végétation et l'ampleur de la différence entre les traitements a augmenté avec le temps. La fertilisation a significativement augmenté la dimension des semis à seulement deux endroits où l'humidité du sol était adéquate; les augmentations étaient très légèrement significatives à un troisième endroit. L'impact de la fertilisation a été moins fort que celui de la maîtrise de la végétation et a eu un effet sur la croissance pendant la première année seulement, tandis que l'effet de la maîtrise de la végétation sur la croissance s'est poursuivi pendant toute la durée de l'étude (4 ans). Il n'y avait pas d'interaction significative entre l'intensité de la maîtrise de la végétation et la fertilisation dans aucun des sites.

[Traduit par la Rédaction]

Introduction

Seedling fertilization has been tried operationally in forestry for several decades but has never become a regular practice in the Pacific Northwest because of mixed results using a variety of fertilizer technologies. Positive responses to early fertilization have been shown in several commercially important Pacific Northwest conifer species including Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), (Strothmann 1980; Carlson and Preisig 1981; van den Driessche 1988), ponderosa pine (*Pinus ponderosa* Dougl. ex P. Laws. & C. Laws.) (Powers and Ferrell 1996), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Carlson 1981; Arnott and Burdett 1988; Radwan et al. 1991). However, fertilization does not always increase growth. For example, poor or negative responses to seedling fertilization have been reported for Douglas-fir (Crouch and Radwan 1981; White and Newton 1990; Roth and Newton 1996). In all three of these studies, urea as a N source was used as a surface-applied fertilizer and resulted in either increased mortality, little effect on conifer growth, or an increased level of competition. We are unaware of any published research on the effect of early fertilization on coastal redwood (*Sequoia sempervirens* (D. Don) Endl.), the fourth species we discuss in this study.

Eliciting a positive response to early fertilization depends on a variety of factors, including fertilizer formulation, rate and placement of fertilizer; stock type, site characteristics, and, of special interest to this paper, vegetation control (Brockley 1988). In the Pacific Northwest, good weed control may be critical to a positive response to early fertiliza-

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tion (Arnott and Burdett 1988; van den Driessche 1988; White and Newton 1990; Powers and Ferrell 1996). In other regions (southeastern United States and Australia), fertilization has increased growth in the absence of vegetation control on some sites (Tiarks and Haywood 1986; Swindel et al. 1988; Haywood and Tiarks 1990; Woods et al. 1992) but must be linked with vegetation control to elicit a positive response on others (Mason et al. 1993; Haywood et al. 1997). In both cases, fertilization combined with vegetation management increased growth more than did vegetation management alone. Early fertilization can be accomplished with a variety of fertilizer products. The use of slow- or controlled-release fertilizers to aid reforestation efforts gained some attention in the 1980s (Carlson and Preisig 1981; Arnott and Burdett 1988; Brockley 1988; van den Driessche 1988). Hauck (1985) provides an excellent review of the different slow-release technologies available. As the growing season progresses in the Pacific Northwest, soils continue to dry. If soluble fertilizers are used, salt concentrations tend to increase, often to the point where they damage seedling roots. Isobutylidene diurea (IBDU) is a slowly soluble compound that is not toxic to plants, does not suppress microbial activity, and provides a continual source of N as it releases through chemical hydrolysis (Hamamoto 1968; Hauck 1985; Wang and Alva 1996). This fertilizer was marketed as Woodace® (Vigoro Industries Inc., Fairview Heights, Ill.) at the time of this study and was specifically designed to be used with newly planted seedlings. It comes as a 3–4 cm diameter briquette that can be added to the planting hole at the time of planting. All the major macro- and micronutrients are incorporated into these briquettes.

To date we are aware of only two published studies to evaluate IBDU as a possible nutrient source in the reforestation environment. One of these was located in South Australia with *Pinus radiata* Donn. ex D. Don (Nambiar and Cellier 1985) and the other in the Pacific Northwest with Douglas-fir (Atalla 1987). Nambiar and Celliar (1985) were not able to identify a response to IBDU fertilization, while Atalla (1987) did. Atalla (1987) placed the fertilizer in the hole at the time of planting, while Nambiar and Celliar (1985) dibbled the fertilizer to the side of the planted seedlings.

In this paper we present results from a series of stand-alone experiments that were designed to assess the interactive effects between different levels of vegetation control and IBDU fertilization via Woodace® controlled-release fertilizer briquettes. The basic study design was repeated with four commercially important conifer species (twice with Douglas-fir) in locations climatically suited to each species, for a total of five independent experiments.

Materials and methods

Site descriptions

Douglas-fir (PSME)

Vernonia-PSME

The Vernonia site is approximately 16 km northwest of Vernonia, Oreg. Before harvest, the site consisted of an approximately 50-year-old stand of Douglas-fir on a slightly sloping northwest aspect. The site had been shovel harvested and slash piled the summer before planting. Soils are deep, somewhat poorly drained, silt loams in the Mayger series, formed in residuum and colluvium derived dominantly from shale. Two-year-old bare-root 1+1 seedlings were planted in the plots in spring 1995. At the time of planting, the site was essentially devoid of plant cover. Over the first 3 years the principal plant competitors were a combination of annual and perennial forbs (*Senecio sylvaticus* L., *Cirsium vulgare* (Savi) Tenore, and *Pteridium aquilinum* (L.) Kuhn) and grasses (chiefly *Holcus lanatus* L.) (Table 1).

Drain-PSME

The Drain site was established on a 70% slope with a southern exposure, 24 km southwest of Drain, Oreg. The previous stand, primarily 50- to 60-year-old Douglas-fir, had been cable harvested the summer before planting. Soils are in the Atring-Larmine complex, which are moderately deep and well-drained loams formed in colluvium from weathered sandstone and siltstone. In February 1996, the site was planted with 2-year-old bare-root 1+1 Douglas-fir seedlings. At the time of planting, few green plants were evident. Over the duration of the study the principal competitors on the site were annual and perennial forbs (*Cirsium vulgare*, *Senicio sylvaticus*, *Hypochaeris radicata* L.) and grasses (chiefly *Holcus lanatus* and *Cynosurus echinatus* L.) (Table 1).

Ponderosa pine (PIPO)

Klickitat-PIPO

The Klickitat site was established in an abandoned Douglas-fir progeny site, approximately 13 km southwest of Glenwood, Wash., that had failed because of a localized frost pocket. Ponderosa pine that had reinvaded this site were removed immediately before installation. The soils are in the Para series and are fine-loamy mixed mesic soils. Two-year-old P+1 bare-root seedlings were planted in mid-March 1995 in the designated plots. Perennial (*Lathyrus* spp. and *Apocynum androseaemifolim* L.) and annual forbs (*Madia gracilis* (J. E. Smith) Keck and *Epilobium paniculatum* Nutt.) and grasses (chiefly *Bromus tectorum* L.) dominated the site at the time of planting and continued to make up the main competition during the study (Table 1).

Coastal redwood (SESE)

Arcata-SESE

The Arcata site was located approximately 25 km inland from the northern California coast, near Korbel. The previous stand was dominated by a second-growth stand of 60- to 70-year-old coastal redwoods. Soils are in the Hugo-Mendocino complex, which are well-drained, gravelly sandy loams formed in sedimentary rock of conglomerate and sandstone. The site is located on a natural ecotone between typically native redwood stands and stands containing more Douglas-fir. The site is on a 30% south facing slope and had been burned the fall before planting. Three-year-old 2+1 bare-root seedlings derived from a single clonal stock were planted in the plots in mid-March 1996. The site was devoid of green plants at the time of planting. This site was marginal and somewhat arid for redwood reforestation. Within the first year a robust herbaceous plant community developed which was dominated by *Cirsium vulgare*, *Trifolium* spp., and a variety of grasses (*Holcus lanatus* and *Cynosurus echinatus*).

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Table 1. Mean cover percentage of the most abundant herbaceous and shrub species in years 1, 2, and 3 in the check treatments at each site.

Site and growth form	Species	Cover (%)		
		Year 1	Year 2	Year 3
Vernonia				
Herbs	Grass species	27.05	53.00	31.00
	Senicio sylvaticus	25.00	1.50	0.70
	Cirsium vulgare	3.70	5.40	7.70
	Pteridium aquilinum	3.20	8.30	13.40
	Hypochaeris radicata	0.20	5.50	20.60
	Rubus ursinus	2.09	7.48	9.61
Shrubs	*Gaultheria shallon*	1.00	1.00	1.60
	Symphoricarpos albus	1.00	3.00	5.20
	Corylus cornuta	0.60	1.20	2.40
Drain				
Herbs	Grass species	8.10	19.00	Not recorded
	Cirsium vulgare	7.30	9.30	Not recorded
	Senicio sylvaticus	7.70	7.70	Not recorded
	Collomia heterophylla	7.50	0.00	Not recorded
	Hypochaeris radicata	2.50	11.00	Not recorded
	Rubus ursinus	1.90	4.70	Not recorded
Shrubs	*Gaultheria shallon*	3.00	3.60	Not recorded
	Symphoricarpos albus	1.00	1.40	Not recorded
Klickitat				
Herbs	Grass species	Not recorded	62.00	37.20
	Lathyrus spp.	Not recorded	5.30	6.10
	Madia gracilis	Not recorded	5.60	12.60
	Epilobium paniculatum	Not recorded	1.70	4.30
	Rumex spp.	Not recorded	3.10	5.30
	Apocynum androsaemifolium	Not recorded	2.80	2.20
Shrubs	*Symphoricarpos albus*	Not recorded	14.80	16.60
	Berberis nervosa	Not recorded	4.30	5.50
	Rosa gymnocarpa	Not recorded	1.40	1.30
Arcata				
Herbs	*Cirsium vulgare*	29.40	11.60	Not recorded
	Trifolium spp.	27.90	6.10	Not recorded
	Grass species	15.80	49.90	Not recorded
	Rubus ursinus	5.00	6.60	Not recorded
	Senicio sylvaticus	4.60	5.80	Not recorded
	Hypochaeris radicata	1.50	7.50	Not recorded
Shrubs	*Ceanothus thyrsiflorus*	1.00	3.10	Not recorded
	Rhus diversiloba	1.40	2.80	Not recorded
	Sequoia sempervirens	5.60	7.00	Not recorded
Seaside				
Herbs	*Montia sibirica*	4.40	1.80	Not recorded
	Oxalis oregana	2.10	6.00	Not recorded
	Erichtites minima	1.00	8.90	Not recorded
	Carex spp.	1.00	2.20	Not recorded
	Senicio sylvaticus	0.10	1.90	Not recorded
	Digitalis purpurea	0.10	11.40	Not recorded
Shrubs	*Rubus spectabilis*	0.90	2.20	Not recorded
	Alnus rubra	0.90	0.25	Not recorded
	Rubus laciniatus	0.50	1.10	Not recorded
	Sambucus racemosa	0.50	4.50	Not recorded

Western hemlock (TSHE)

Seaside-TSHE

The Seaside site is located 8 km east of Seaside, Oreg., on a 60% south-southeast slope. The previous stand was a mix of 40- to 60-year-old western hemlock, Sitka spruce (*Picea sitchensis* (Bong.) Carrière), and red alder (*Alnus rubra* Bong.). The soil is in the Hootchie-Necanicum complex and

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Table 2. Crop trees, study site locations, site characteristics, and herbicide and rates used for vegetation control.

Conifer species	Study site	Planted (spring)	Elevation (m)	Annual precipitation (cm)	Site index (m at 50 years)	Herbicide used (kg a.i./ha)
Douglas-fir	Vernonia	1995	213	140–165	35	Sulfometuron (0.16)
	Drain	1996	93	100–130	32	Hexazinone (1.68)
Ponderosa pine	Klickitat	1995	701	76–90	27	Hexazinone (1.68)
Coastal redwood	Arcata	1996	76	64–76	31	Atrazine, year 1 (4.5)
						Sulfometuron, year 2 (0.16)
Western hemlock	Seaside	1996	31	190–230	34	Hexazinone (1.68)

is a deep to moderately deep, well-drained silt loam formed in colluvium derived from basalt. Two-year-old P+1 bareroot seedlings were planted in the plots in mid-February 1996. Because of a thick organic layer, which is common in coastal western hemlock stands, vegetation was slow to invade. What vegetation that did invade was mainly herbaceous in habit (*Digitalis purpurea* L., *Erichtites minima* (Poir.) DC., and *Oxalis oregana* Howell) (Table 1).

Experimental design

The study was a completely randomized design of six treatment levels, with the plot being the treatment unit; this design was repeated on five sites with four species of crop trees: Douglas-fir, ponderosa pine, western hemlock, and coastal redwood (Table 2). Because of large differences in slope across the Arcata-SESE site, the design was slightly altered to a randomized block design (blocked by position on the slope) with four blocks serving as replications, rather than a completely randomized design.

Two sites, Vernonia-PSME and Klickitat-PIPO, were established in 1995; the other three were established in 1996. Each site contained four replications of each of six randomly assigned separate treatments (24 plots). Each treatment plot consisted of 36 conifer seedlings planted at a 3 × 3 m spacing and surrounded by a one-tree buffer row. Plots were laid out as contiguously as possible.

Treatments

Treatments consisted of three levels of vegetation control, factorially overlaid with two fertilization treatments, for a total of six treatments.

Weed control

The three vegetation-control treatments were a check (no weed control), 1.5 m^2 of weed control, and 3.3 m^2 of weed control. Weed control was centered on each test seedling and achieved with herbicides that differed in active ingredient and rate, depending on the site (Table 2). This required two applications, once each spring in the first and second year except at the Klickitat-PIPO site, where the application of hexazinone in year 1 maintained near weed free conditions within the treated area for 2 years. Different herbicides were used among sites, because there was no one herbicide that was expected to give satisfactory control of competing vegetation at all sites with reasonable assurance of conifer safety. We instead opted for using the herbicide most commonly used by operational foresters in the regions the study sites were located with the goal being to achieve the desired area of vegetation control and maintain it for two growing seasons.

Fertilization

The treatments were no fertilizer or fertilization with two different Woodace®, IBDU (isobutylidene diurea) slow-release briquettes placed in the bottom of each planting hole. The formulations of the two briquettes were 14:3:3 (N:P:K) and 9:9:4 with micronutrients (Table 3). The combination of these two briquettes was chosen based on satisfactory response observed in anecdotal observations from operational field trials. The fertilizer treatment was intended to provide continuous and complete nutrition to the growing seedlings for 18 months. A thin layer of soil was placed over the briquettes before the seedling was planted to prevent root burn.

Measurements

Seedlings

One month after planting, survival of the trees was assessed and initial height and basal diameter of survivors were measured. Seedling height and diameter were remeasured each fall through 1998.

Vegetation

Eight seedlings from each plot were chosen randomly once a year during the peak of the vegetative cover on the site (late July to early August). Vegetation cover within a 1.2-m radius (vegetation assessment plot) around each of these seedlings was derived from an ocular estimate using a polyvinylchloride pipe quadrant gid. The vegetation assessment plot was designed to be larger than the treatment plots so that cover among treatments could be effectively compared using a consistent measure. Only measuring the cover within the treated area would have resulted in a biased estimate of competing vegetation, i.e., similar levels of cover in the smaller treatment areas would not be comparable with the same cover in larger treatment areas, because cover further from a seedling can be expected to have less impact than closer cover. The vegetation-assessment plots were 27% and 67% larger than the 3.3- and 1.5-m^2 vegetation area treatments, respectively (Fig. 1). This procedure was repeated in years 1 and 2 at all sites and in year 3 at the Vernonia-PSME and Klickitat-PIPO sites.

Foliage sampling and nutrient analysis

Foliage was sampled in the fall of years 1 and 2, except at Seaside-TSHE. In mid-October 1995, three trees were selected at random from each treatment plot at Vernonia-PSME and Klickitat-PIPO. All needles were carefully

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Table 3. Nutrient contents of the briquettes used in the fertilization treatment.

	Mass (g)		
Nutrient	14:3:3 formulation	9:9:4 formulation	Combined
Briquette	17	17	34
Nitrogen	2.38	1.53	3.91
Urea	1.02	0.153	1.173
Slow release (IBDU)	1.36	138	2.74
Phosphorus (P_2O_5)	0.51	1.53	2.04
Potassium (K_2O)	0.51	0.68	1.19
Ca	0.34	0.51	0.85
Mg	0.17	0.17	0.34
S	0.17	0.17	0.34
Cu	0.17	0.102	0.272
Fe	0.17	0.17	0.34
Mn	0.039	0.051	0.09
Zn	0.0187	0.0238	0.0425
B	Not listed	Not listed	

stripped from each seedling and dried. A random subsample of 100 Douglas-fir needles or 90 individual ponderosa pine needles (not fascicles) from each tree were dried and weighed. All the needles from each tree were ground and concentrations of N (total Kjeldhal nitrogen), P, K Ca, Mg, and B were determined by chemical analysis using standard laboratory procedures. In mid-October 1996, foliage was sampled at Vernonia-PSME, Klickitat-PIPO, Drain-PSME, and Arcata-SESE by a different procedure. A sample of current-year foliage was snipped off eight randomly selected trees in each plot at all sites. The collections were pooled by plot and site. Again, 100 needles from the Douglas-fir samples and 90 from ponderosa pine were counted, dried, and weighed. All samples were analyzed chemically as before except that samples at Drain were not analyzed for Mg. The coastal redwood samples were handled slightly differently. Because redwood does not exhibit determinate growth, the total number of leaflets collected were counted and dried; a mean mass per leaflet was determined mathematically. They were then analyzed in the same way as the other samples. This procedure was repeated in 1997 at Arcata.

No foliage samples were collected from the Seaside-TSHE site in year 1, because the seedlings were very small and we feared that removing foliage would damage seedlings to the point that growth results would be confounded. Because we lacked first-year data we decided not to sample foliage in year 2 at this site. Foliage was not collected in year 2 at Drain-PSME as a cost-saving measure.

Statistical analysis

Each site was analyzed independently. A repeated measures analysis using the MIXED procedure in the SAS statistical software package was used. Plot means for basal diameter, seedling height, and conical stem volume ((basal diameter)^2 × height × π/12) from years 1–4 at the Vernonia-PSME and Klickitat-PIPO sites and through year 3 at all the other sites were assessed for differences by treatment. The analyses used a factorial model with three levels of vegetation control and two levels of fertilization treatments. For each independent analysis several covariance matrix structures were applied, and we settled on the structure resulting in the largest Akaike information criterion value (Littell et al. 1996)

Initial basal diameter and seedling height were included in the repeated measures model but later removed. The lack of differences at time zero and large differences in future years always resulted in year × treatment interactions that masked the occurrence of future year × treatment interactions. With initial mean size removed from the model, any year × treatment interactions could be more appropriately assessed. An independent ANOVA analysis was performed to insure that initial basal diameter and seedling height did not vary by treatment. Natural log transformations of basal diameter, height, and stem volume and an arcsine square-root transformation of mortality percentage was required to meet the assumptions of equal variance. Data reported have been back transformed.

Seedling mortality was high at all sites because of a variety of stochastic events independent of treatment. Three plots at the Vernonia-PSME site were removed because of extreme mortality resulting in three replications of the fertilized 1.5-m^2 treatment and the unfertilized 3.3-m^2 and check treatments. One plot was removed at the Drain-PSME site, because it was oversprayed during an operational herbicide application adjacent to the study area resulting in three replications of the unfertilized check treatment at this site. The high mortality resulted in wider than desired spacing among seedlings at some sites. However, even in plots with no mortality, intertree competition was not a factor influencing growth as of year 4. We hypothesized that seedlings in plots with fewer than 36 trees continued to behave similarly to seedlings in fully stocked plots. A regression analysis of plot mortality by plot means was performed to test and confirm this hypothesis. Finally, the weed-control treatments did not always result in the desired area of weed control at every site. To assess the importance of weed pressure at each site and among sites, we performed a regression analysis modeling mean final year stem volume by a weed cover index (sum of cover in year 1 and cover in year 2) and compared slopes of regression lines among the five sites.

Mean vegetation cover, nutrient concentration, and needle mass data were analyzed using ANOVA independently by site and year of data collection. Again, a factorial model including weed-control area and fertilization was used as stated above. In analysis of variance, orthogonal contrasts were used to partition mean differences among treatments as follows: (*i*) fertilized versus unfertilized; (*ii*) no weed control versus weed control; and (*iii*) 3.3 m^2 weed control versus 1.5 m^2 of weed control. Residuals from the analyses were examined, and no transformations were required.

Results

At four of the five sites, mean stem volume increased with increasing area of weed control, and the magnitude of difference between treatments increased with time (Fig. 2). Fertilization significantly increased stem volume only at the two sites with adequate soil moisture (Vernonia-PSME, p = 0.024; Seaside-TSHE, p = 0.0027). Response to fertilization was less than from weed control and impacted growth for only the first year, whereas the influence of weed control continued to influence growth the entire length of the study

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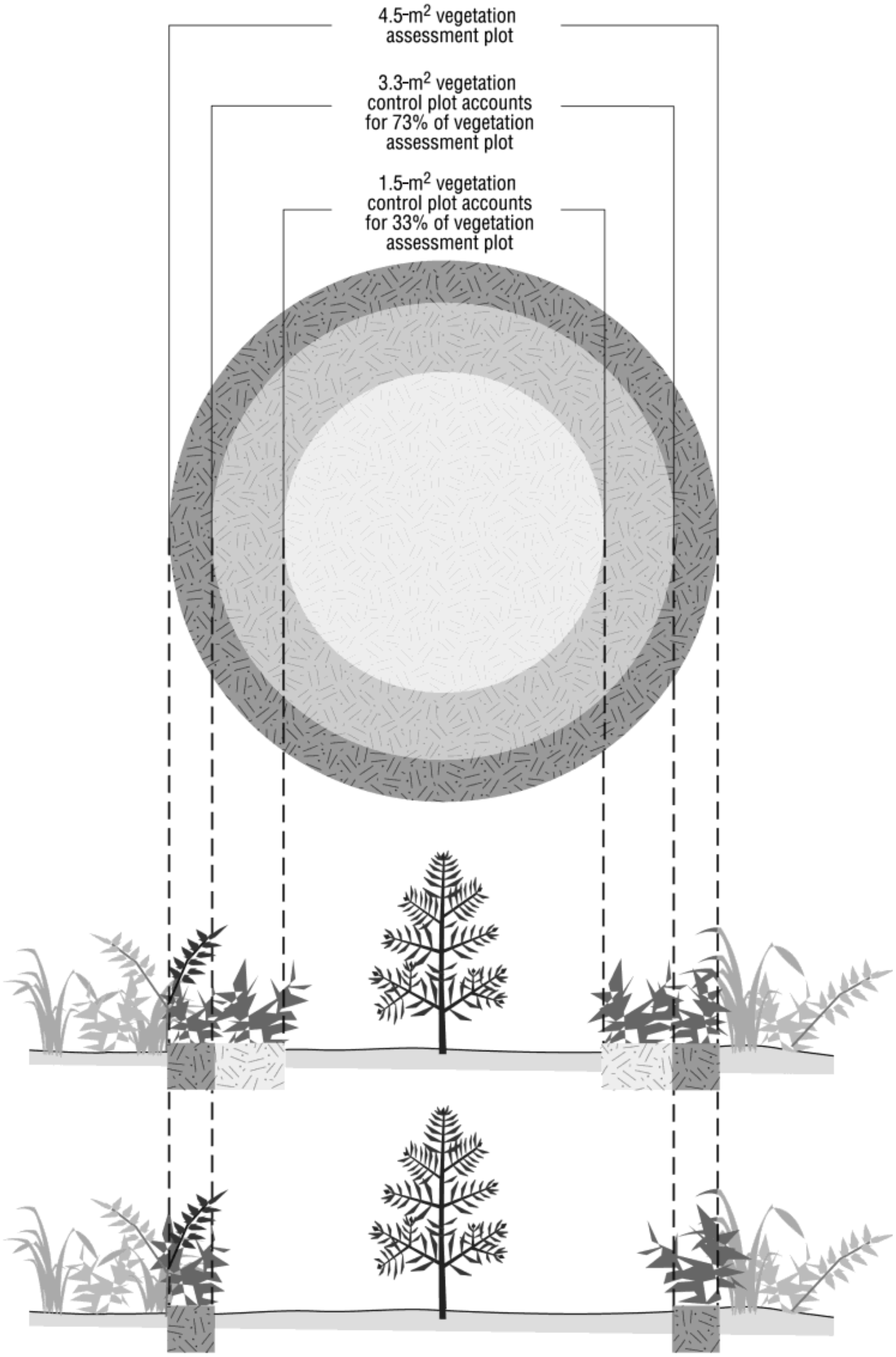
Fig. 1. Depiction of vegetation-control treatments and the vegetation-assessment plots.



(4 years). Area of vegetation control and fertilization did not interact significantly at any site. A linear relationship between cumulative cover index and final-year stem volume was found at each site examined. However, the slope of this linear relationship differed by site ($p < 0.005$).

Douglas-fir

Vernonia-PSME site

Stem volume, basal diameter, and stem height exhibited a year × weed control treatment interaction (Figs. 2–4). The interaction resulted because the difference in seedling size among weed-control treatments increased each year of the study. After 1 year, stem volume and basal diameter were 68 and 23% greater in the 3.3-m^2 treatment than in the check treatment, respectively (Fig. 2). This difference continued to increase with time, and by year 4, mean stem volume and basal diameter had increased to 149 and 31% greater in the 3.3-m^2 treatment than in the check, respectively. Stem height was influenced less than stem volume or basal diameter, and a significant ($p = 0.0092$) increase in height was not

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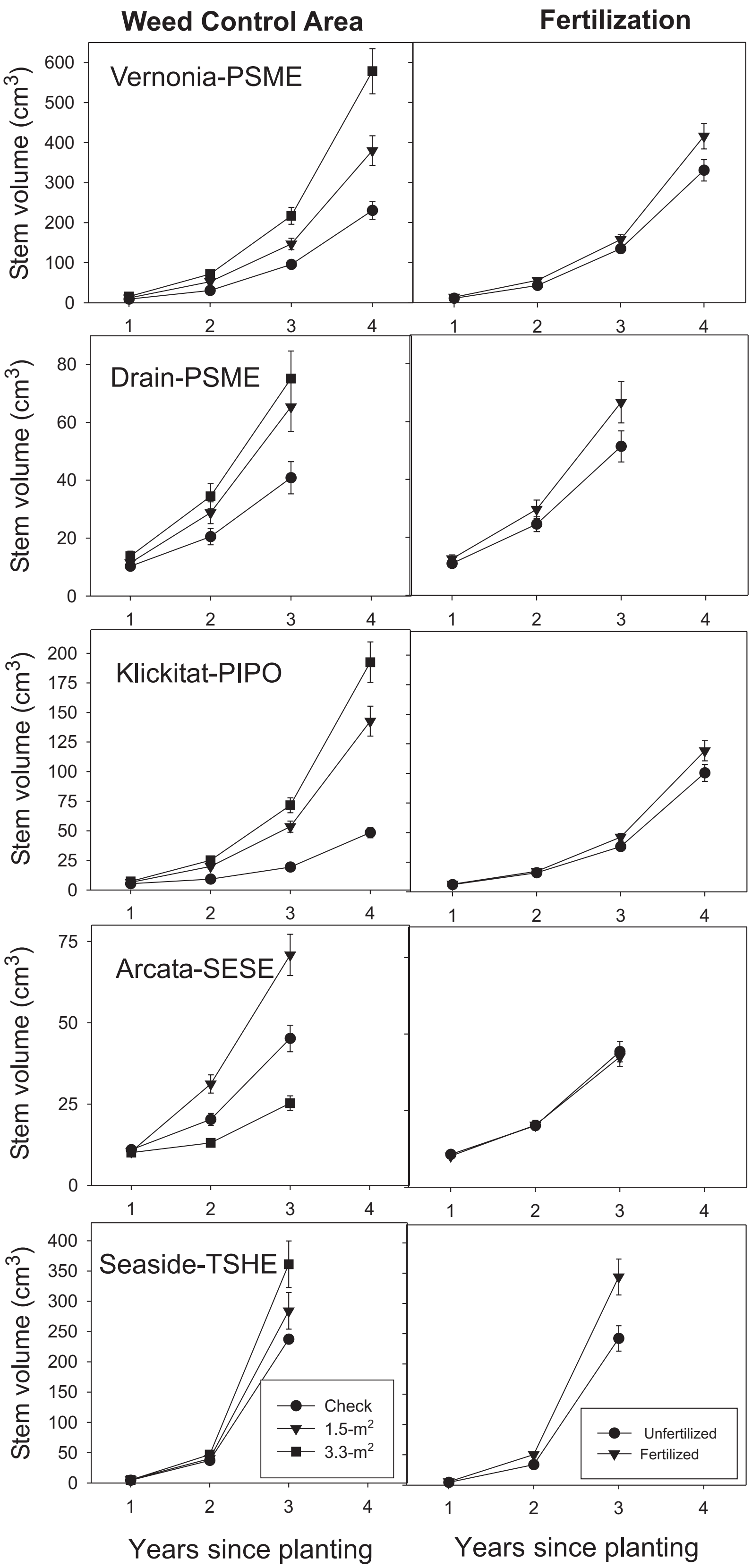
Fig. 2. Back-transformed conical stem volume means for weed control area treatments and for fertilization treatments at all five study sites. Error bars are SEs from a least-square means comparison.



Treatment	p value
Weed control (W)	0.0001
Fertilization (F)	0.0242
W x F	0.4415
Year (Y)	0.0001
W x Y	0.0070
F x Y	0.1928

Treatment	p value
Weed control (W)	0.0172
Fertilization (F)	0.1205
W x F	0.8747
Year (Y)	0.0001
W x Y	0.4111
F x Y	0.7891

Treatment	p value
Weed control (W)	0.0001
Fertilization (F)	0.1691
W x F	0.4026
Year (Y)	0.0001
W x Y	0.8741
F x Y	0.3118

Treatment	p value
Weed control (W)	0.0001
Fertilization (F)	0.7137
W x F	0.3884
Year (Y)	0.0001
W x Y	0.2240
F x Y	0.2814

Treatment	p value
Weed control (W)	0.0982
Fertilization (F)	0.0027
W x F	0.4766
Year (Y)	0.0001
W x Y	0.2871
F x Y	0.0936

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Fig. 3. Back-transformed basal diameter means for weed control area treatments and for fertilization treatments at all five study sites. Error bars are SEs from a least-square means comparison.

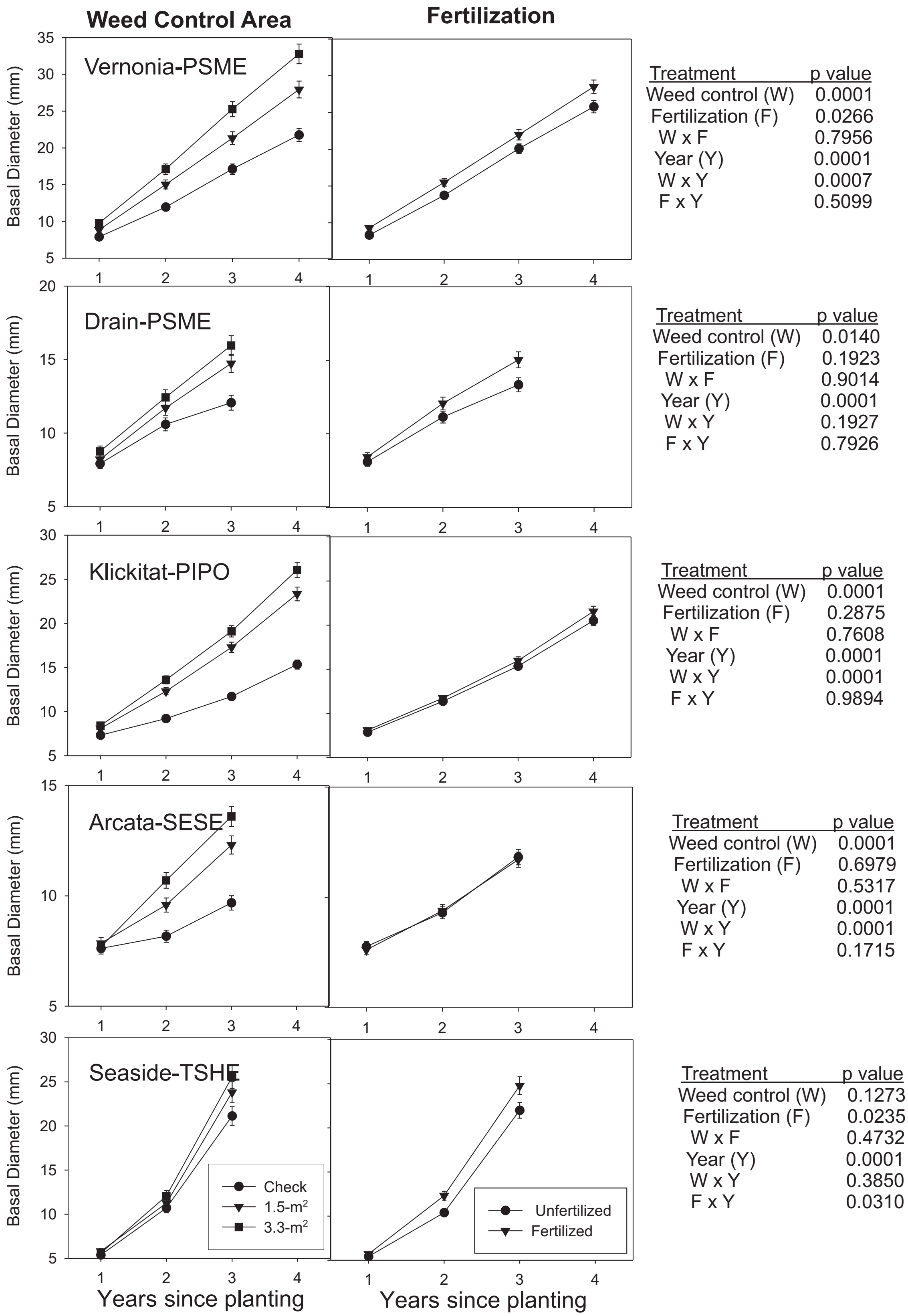

Fig. 4. Back-transformed conical height means for weed control area treatments and for fertilization treatments at all five study sites. Error bars are SEs from a least-square means comparison.

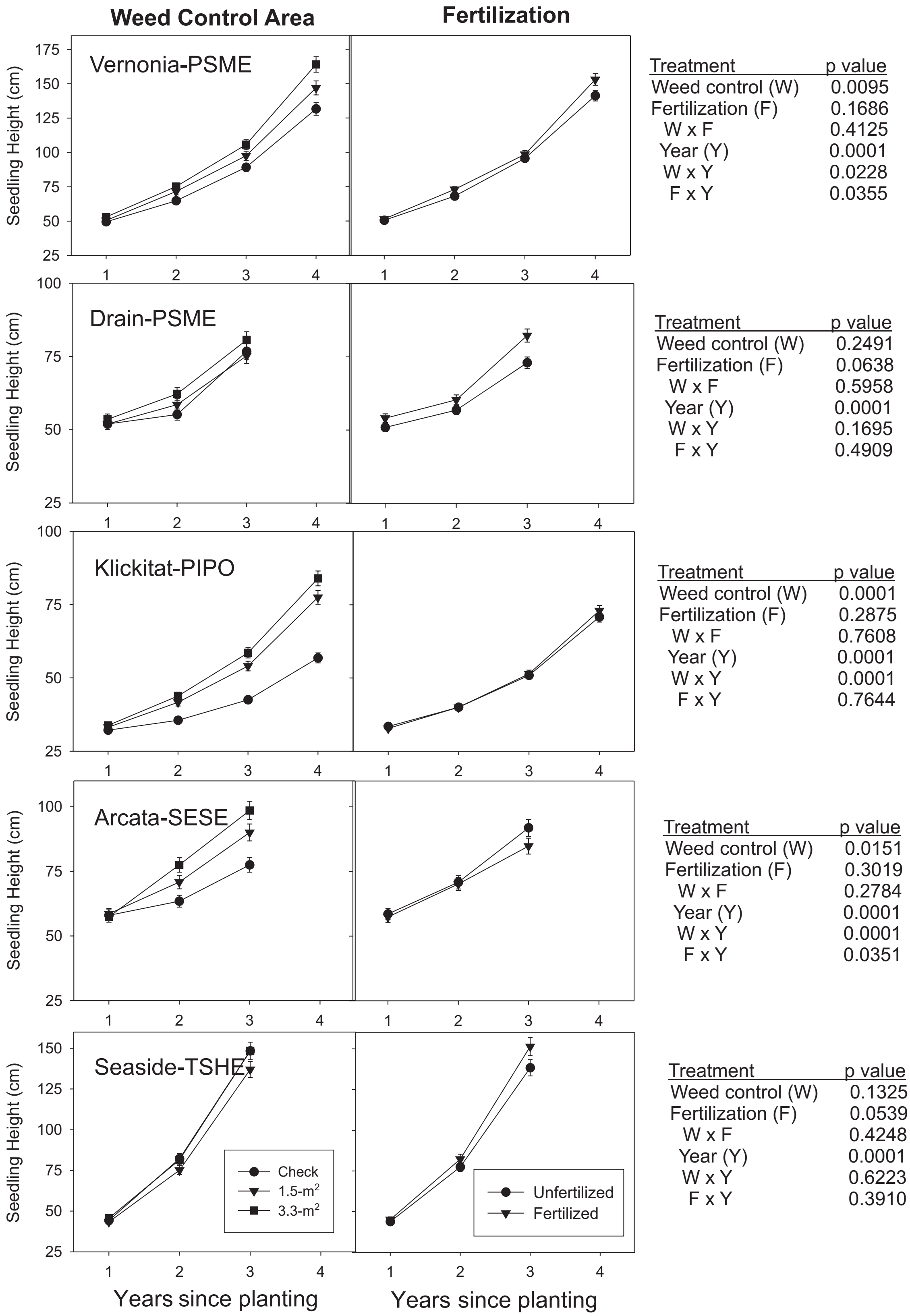

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Fig. 5. Back-transformed mean percent mortality for weed control area treatments and for fertilization treatments at all five study sites. Error bars are SEs from a least-square means comparison.

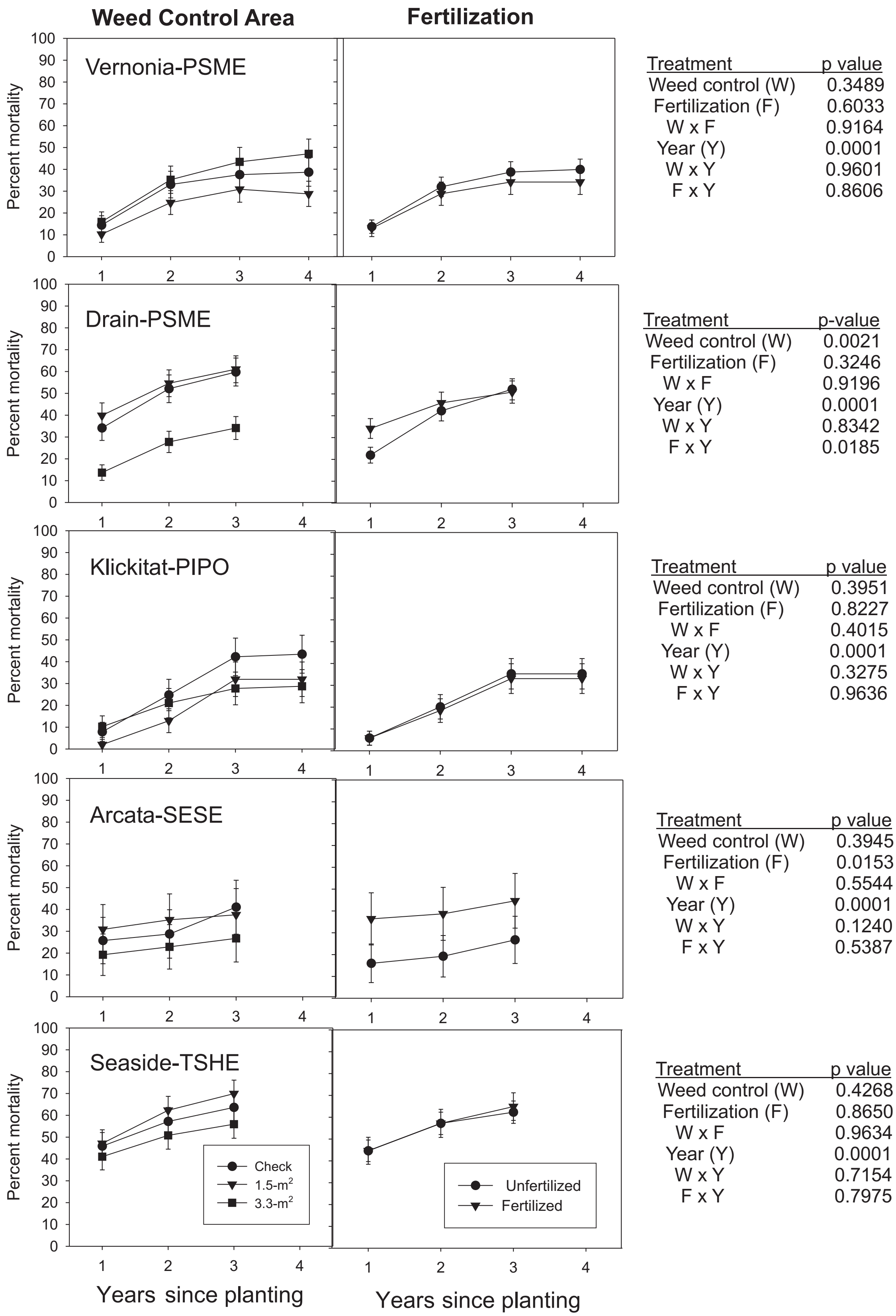

Table 4. Mean percentage cover by weed-control treatment for each site.

Site and treatment	Vegetation cover (%)		
	Year 1	Year 2	Year 3
Vernonia-PSME			
Check	65	80	83
1.5 m^2	37	52	76
3.3 m^2	14	23	64
Drain-PSME			
Check	47	75	na*
1.5 m^2	40	64	na
3.3 m^2	27	53	na
Klickitat-PIPO			
Check	84	90	79
1.5 m^2	72	81	79
3.3 m^2	67	73	79
Arcata-SESE			
Check	72	92	na
1.5 m^2	69	79	na
3.3 m^2	60	64	na
Seaside-TSHE			
Check	17	45	na
1.5 m^2	17	25	na
3.3 m^2	11	13	na

*Not applicable.

observed until year 2, and by year 4 the 3.3-m^2 treatment was 25% greater in height than the check (Fig. 4). Mortality was unaffected by weed-control treatment (Fig. 5).

Vegetation cover differed as expected among the weed-control treatments (Table 4). Although vegetation cover tended to increase into the second and third year, differences among treatment levels were still apparent even through year 3. Cumulative cover index was negatively correlated ($p < 0.0001$) with stem volume and explained 60% of the variance in stem volume in year 4.

Fertilization had less impact on stem volume, basal diameter, and stem height than did weed control (Figs. 2–4). A year × fertilizer interaction was evident for only stem height. Stem volume and basal diameter was larger in fertilized plots than unfertilized in all 4 years of measurements. This difference increased slightly but not significantly with time. Fertilization had resulted in a 26 and 10.5% increase in stem volume and basal diameter after 4 years of growth, respectively. Height was less responsive to the fertilizer treatments and only differed at a marginally significant level ($p \leq 0.1$) in year 2 and year 4. By year 4, mean stem height was 7.8% (11 cm) greater in the fertilized than in the unfertilized plots. Seedling mortality was unaffected by fertilization or weed control (Fig. 5).

After 1 year of growth, concentrations of all the foliage nutrients had dropped from levels measured coming from the nursery (Table 5). Fertilizer × weed control interactions were not found for any nutrient in year 1 or 2. Nitrogen was the only foliar nutrient concentration to be significantly (p = 0.05) impacted by the weed-control treatments, increasing if weed control was applied. No differences in N concentration were found between the 3.3- and 1.5-m^2 treatments. Potassium and Mg levels were not different between the check and weed-control treatments but were higher in the 1.5-m^2 treatment than in the 3.3-m^2 treatment.

First-year B concentration was greater (p = 0.001) in seedlings from the fertilized plots than those from unfertilized plots. No other nutrient concentration was affected by fertilization. Needle mass interacted significantly (p = 0.008) between the fertilizer and weed-control treatments in year 1 with the fertilized 1.5-m^2 treatment resulting in considerably greater needle mass than any other treatment. In no treatment did needle mass approach that measured at lifting from the nursery.

Second-year foliar B concentrations were lower (p = 0.003) in the weed-control treatments than the check and less (p = 0.026) in the 3.3-m^2 treatment than in the 1.5-m^2 treatment. No other nutrient concentration varied by weed-control treatment in year 2. In year 2, B concentrations continued to be larger (p = 0.004) in the fertilized treatment than in the unfertilized, although the difference in concentration was less than in year 1 (Table 5). Differences in P concentrations were also present (p = 0.035) with the unfertilized treatments having a greater P concentration than fertilized treatment in year 2.

Drain-PSME site

The vegetation-control treatments significantly impacted stem volume (p = 0.0172) and basal diameter (p = 0.014) and did not interact significantly with time (Figs. 2 and 3). The check treatment was significantly (p = 0.0058) less than the weed-control treatments, while the 1.5- and 3.3-m^2 treatments did not differ (p = 0.3261). No differences in stem height were detected among the weed-control treatments nor was an interaction with time evident. This site experienced an extremely dry establishment year resulting in larger than normal mortality losses. Seedling mortality was impacted significantly by vegetation-control treatment. The check treatment did not differ from the weed-control treatments; however, the 3.3-m^2 treatment had significantly less mortality than the control (Fig. 5).

The weed-control treatments resulted in the desired areas of spot weed control at this site and significant differences among treatments were observed in years 1 and 2 (Table 4). Cumulative cover index was significantly correlated (p < 0.0001) and explained 47% of the variability stem volume (Fig. 5).

Fertilization did not result in differences in stem volume, basal diameter, or height nor interact significantly with time for any of these parameters. However, for seedling mortality a significant (p = 0.0185) interaction between fertilization and time was found. The fertilized plots had a greater mortality in year 1 (p = 0.031); however, by year 3, no differences between the two fertilizer treatments were evident (p = 0.975) (Fig. 5).

After the first growing season, foliar nitrogen concentrations were greater (p = 0.005) in the weed-control treatments than the check, but no difference between the 1.5- and 3.3-m^2 treatment was found (p = 0.092). Concentration of no other nutrient differed by weed-control treatment in year 1.

In year 1, foliar N concentrations were greater (p = 0.001) in fertilized plots than unfertilized, while foliar P concentrations were lower in the fertilized plots (p = 0.01) (Table 3). No other differences in foliar concentration were observed. Needle mass was unaffected ($p \geq 0.05$) by weed control or

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Table 5. Mean foliar nutrient concentrations and needle mass (NM) in years 1 and 2 at all but the Seaside site.

Site and treatment	Year 1 N (%)	P (%)	K (%)	Ca (%)	Mg (%)	B (ppm)	NM (g)	Year 2 N (%)	P (%)	K (%)	Ca (%)	Mg (%)	B (ppm)	NM (g)
Vernonia-PSME														
Nursery	1.79	0.3	0.83	0.3	0.46	34.0	0.35							
Unfertilized check	1.39	0.22	0.56	0.18	0.11	14.2	0.23	1.41	0.21	0.70	0.26	0.09	12.0	0.56
1.5 m^2	1.61	0.27	0.64	0.21	0.13	19.5	0.26	1.47	0.19	0.70	0.24	0.09	11.5	0.70
3.3 m^2	1.77	0.21	0.51	0.21	0.10	13.1	0.29	1.55	0.18	0.67	0.28	0.08	8.8	0.67
Fertilized check	1.37	0.21	0.56	0.20	0.10	31.3	0.22	1.44	0.18	0.72	0.25	0.08	17.1	0.62
1.5 m^2	1.68	0.21	0.60	0.23	0.12	22.4	0.37	1.45	0.16	0.71	0.27	0.08	13.5	0.69
3.3 m^2	1.65	0.23	0.52	0.24	0.11	26.7	0.24	1.49	0.18	0.67	0.29	0.08	10.8	0.65
Drain-PSME														
Nursery	1.9	0.2	0.81	0.36	0.13	20.2	0.32							
Unfertilized check	1.17	0.15	0.57	0.17		15.5	0.21							
1.5 m^2	1.49	0.24	0.72	0.21		12.0	0.27							
3.3 m^2	1.37	0.16	0.59	0.18		11.5	0.22							
Fertilized check	1.92	0.18	0.60	0.26		8.0	0.25							
1.5 m^2	1.92	0.14	0.81	0.86		16.7	0.28							
3.3 m^2	2.47	0.12	0.51	0.33		16.0	0.24							
Klickitat-PIPO														
Nursery	1.86	0.66	0.83	0.5	0.47	57.9	3.84							
Unfertilized check	1.23	0.15	0.62	0.08	0.09	6.38	1.33	1.08	0.15	.083	0.13	0.10	8.5	2.5
1.5 m^2	1.62	0.16	0.70	0.12	0.09	10.8	1.43	1.13	0.16	0.84	0.13	0.10	8.6	3.56
3.3 m^2	1.75	0.18	0.72	0.12	0.09	11.7	1.81	1.11	0.16	0.82	0.11	0.10	9.9	4.10
Fertilized check	1.43	0.16	0.64	0.13	0.09	20.4	1.48	1.18	0.17	0.83	0.13	0.10	15.0	2.62
1.5 m^2	1.68	0.17	0.74	0.14	0.08	21.2	2.01	1.19	0.15	0.83	0.12	0.10	14.3	3.43
3.3 m^2	1.78	0.17	0.79	0.14	0.09	19.1	1.84	1.11	0.15	0.85	0.11	0.10	11.8	3.79
Arcata-SESE														
Nursery	1.91	0.3	0.85	0.78	0.21	7.8								
Unfertilized check	1.0	0.17	0.46	0.70	0.22	5.5	0.05	1.55	0.31	0.96	0.87	0.22	17.3	0.13
1.5 m^2	0.97	0.15	0.51	0.65	0.25	6.8	0.06	1.61	0.28	0.99	0.71	0.19	16.8	0.12
3.3 m^2	0.98	0.16	0.47	0.75	0.22	8.3	0.06	1.63	0.31	0.93	0.74	0.21	19.0	0.13
Fertilized check	1.03	0.16	0.37	0.62	0.21	7.0	0.03	1.34	0.28	0.87	0.92	0.25	17.8	0.11
1.5 m^2	1.00	0.15	0.47	0.68	0.23	10.1	0.06	1.61	0.28	0.94	0.78	0.21	18.5	0.12
3.3 m^2	1.03	0.16	0.52	0.76	0.24	11.9	0.07	1.65	0.24	0.93	0.72	0.19	19.0	0.14

Note: Foliage was not analyzed at Seaside-TSHE in either year and only in year 1 at Drain-PSME. Concentration of foliar nutrients was analyzed soon after lifting.

fertilization and was considerably below the mass measured at lifting from the nursery.

Ponderosa pine

Klickitat-PIPO site

A significant interaction between the weed-control treatments and year since planting occurred for stem volume, basal diameter, and height ($p \leq 0.0001$) (Figs. 2–4). This interaction resulted from differences in these parameters increasing with time. Stem volume was 36% greater in the 3.3-m^2 treatment than in the check treatment after 1 year and increased to 297% greater by year 4. Differences in basal diameter and height also increased with time but less so than stem volume (Figs. 3 and 4). By year 4, basal caliper was 69% greater and height 48% greater in the 3.3-m^2 treatment than in the check. Mortality was unaffected by the weed-control treatments (Fig. 5).

The herbicide applications were effective in creating spot areas of weed control around the seedlings (Table 4), but these areas were smaller than intended. The 1.5-m^2 treatment in actuality averaged 1.2 m^2, and the 3.3-m^2 treatment averaged only 1.7 m^2. The herbicide application made in year 2 continued to be highly effective over the first 2 years on this site, and because of this a second-year herbicide application was not made. Cumulative cover index was negatively correlated ($p < 0.0001$) and explained 54% of the variance in fourth-year stem volume.

Fertilization had no significant ($p \geq 0.05$) effect on stem volume, basal diameter, height, or mortality at the Klickitat-PIPO site (Figs. 2–4).

Of the nutrients sampled in year 1, N, P, and K foliar concentration were greater ($p = 0.001$, $p = 0.031$, and $p = 0.01$, respectively) in the weed-control treatments than in the check. No other nutrient was significantly influenced by weed control. Foliar concentrations of all nutrients sampled dropped from nursery levels sampled after year 1 (Table 5). Only foliar B concentration increased significantly ($p = 0.001$) with the fertilizer treatment. Mean B concentration for the fertilized treatment was 9.6 versus 20.9 ppm for the unfertilized treatment. Needle mass did not vary significantly with either fertilization or area of weed-control treat-

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ment in year 1 and was considerably below that measured directly from the nursery.

In year 2, no differences in foliar nutrients were observed among the weed-control treatments. Nitrogen concentrations had dropped to 1.1–1.2% across all of the treatments by year 2, and B concentration continued to be greater $p \leq 0.001$) in fertilized plots than in unfertilized plots (Table 5). However, B concentrations had dropped considerably from year 1, to 13.7 ppm in the fertilized treatment and 9 ppm in the unfertilized. Needle mass increased with weed-control treatment in year 2 but did not vary by fertilization treatment. Needle mass for all but the check treatment was near that measured at lifting after 2 years.

Coastal redwood

Arcata-SESE site

Stem volume, basal diameter, and height were impacted by the weed-control treatments and a weed control × year interaction was evident for all three parameters ($p \leq 0.001$). After 1 year of growth, no differences in stem volume, basal diameter, or height were evident, but differences emerged in year 2 and then expanded in year 3. After 3 years the 3.3-m^2 treatment had a stem volume, basal diameter, and height 180, 40, and 27% greater, respectively, than the check treatment. Mortality was unaffected by weed-control treatment (Fig. 5).

Vegetation cover did not differ among weed-control treatments in year 1, because the atrazine herbicide used did not eliminate a low-growing *Trifolium* species that developed ubiquitously across the site (Table 4). Cover ranged from 60 to 72% across the areas treated. The sprayed areas were visually indistinguishable from other unsprayed areas by early summer. In year 2, sulfometuron herbicide was used which created the desired levels of weed control. Cumulative cover index was negatively correlated ($p < 0.0001$) with third-year stem volume and explained 65% of the variance.

Fertilization had no discernable effect on stem volume, basal diameter, or height (Figs. 2–4). Mortality was significantly greater ($p = 0.015$) in fertilized versus unfertilized plots and increased equally in both over the 3 years (Fig. 5).

No significant ($p \leq 0.05$) differences in foliar nutrient concentrations were found in the weed-control or fertilization treatments in year one (Table 5). However, a marginally significant ($p = 0.055$) increase in B was found in fertilized versus unfertilized treatments. Additionally, a marginally significant ($p = 0.062$) decrease in foliar P concentration was found in weed-control treatments versus the check. Mean leaflet mass increased ($p \leq 0.0001$) with area of weed control in the first year but did not vary by fertilization treatment ($p \geq 0.05$).

In year 2, N concentration was greater ($p = 0.001$) in the weed-control treatments than in the check. Additionally, Ca and Mg concentrations declined with weed control. Mean leaflet mass did not differ by weed-control treatment in year 2. The only nutrient to differ in year 2 by fertilization treatment was P ($p = 0.047$), which was less in the fertilized treatment (0.27%) than in the unfertilized treatment (0.30%).

Western hemlock

Seaside-TSHE site

Mean stem volume, basal diameter, height, and mortality did not differ by weed-control treatment (Figs. 2–5). Because vegetation was slow to invade the first-year vegetation-control treatments had little effect on vegetation cover (Table 4). Even in the check treatment, mean vegetation cover was only 17%. The weed-control treatments had a larger effect on vegetation cover in year 2 (Table 4). Prior to harvest this site consisted of a dense western hemlock stand, which, common to many mature coastal hemlock stands, had little understory cover and a very thick organic layer that hindered the invasion of competing vegetation. Cumulative cover was negatively correlated ($p = 0.03$) with third-year stem volume but explained only 17% of its variation.

Stem volume was larger in the fertilization treatment than in the unfertilized and a marginally significant ($p = 0.0936$) year × fertilizer treatment interaction was observed. A significant fertilizer × year interaction was evident ($p = 0.031$) with no difference in diameter being evident after 1 year ($p = 0.102$) but in years 2 and 3, fertilized plot means were significantly greater (year 2, $p = 0.0015$; year 3, $p = 0.0048$) than in the unfertilized plots. After 3 years the fertilized plots were 30% greater in diameter than the unfertilized. Fertilization resulted in a mean height difference that was marginally significant ($p = 0.0539$) and resulted in a 9% gain in stem height after 3 years. Mortality was unaffected by either the fertilizer or weed-control treatments but did increase ($p = 0.0001$) over the 3 years of the study.

Mortality and plot growth

Mortality explained a significant portion of the variability in plot growth at two of the five sites; Drain-PSME, and Klickitat-PIPO. Of these it was a significant predictor of growth for all 3 years at Drain explaining 11, 28, and 25% of variability in years 1, 2, and 3, respectively. At the Klickitat-PIPO site, mortality was a significant predictor of mortality only in years 3 and 4 but explained less than 13% of variability in either year.

Discussion

Spot weed control increased seedling growth at four of the five study sites, supporting findings of other studies (McDonald and Fiddler 1986; Balneaves 1987; Jaramillo 1988; Dougherty and Lowery 1991; Oester et al. 1995; Richardson et al. 1996; Rose et al. 1999). In three of the four sites showing weed-control responses, basal diameter differences among treatments became more pronounced with time, resulting in significant interactions between area of weed control and year since planting. Of the five sites investigated, the best overall growth was found at the sites with the greatest annual precipitation: Vernonia-PSME and Seaside-TSHE. The only site not showing a strong response to area of weed control was Seaside where competing vegetation was slow to establish, and differences in cover between weed-control treatments were small.

Seedlings at the five sites responded in an inverse linear fashion to differences in cumulative cover created by the weed-control treatments. When compared the slopes of these lines were found to differ among the five sites. This was not surprising given that comparisons were made across different crop species and extreme differences in temperature, rainfall, soils, planting year, and competing species at the five sites examined.

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Other investigators examining the effects of plant cover on Douglas-fir and ponderosa pine have demonstrated that most of the gains are made when cover is reduced to 0–30% (Wagner et al. 1989; Wagner and Radosevich 1991*a*). Comparisons of our cover data to these numbers are problematic, because we did not use broadcast weed-control treatments. It is likely that seedlings still faced competition from vegetation outside the areas treated (Wagner and Radosevich 1991*b*). Our results are within the range reported by Rose et al. (1999) for Douglas-fir growth response measured in similar areas of weed control. In an effort to use a consistent measure of cover to make comparisons among treatments we included the weed-control area and some area outside this area that was unaffected by the herbicide treatment. Thus, even when we achieved excellent weed control in the 3.3-m^2 treatment area we would expect to still measure a significant weed cover level beyond this interior area (Fig. 1). Simply assessing competition within the treated area alone would have confounded competition comparisons between different area plots. Our results further support the huge volume of published literature demonstrating greater levels of conifer growth with increased weed control. What is more interesting is that we measured a growth response to weed control across a large gradient in site quality except where little vegetation invaded during the period of active weed control.

Fertilization resulted in a significant seedling growth response only at Vernonia-PSME and Seaside-TSHE; response was marginally significant at Drain-PSME. Because all of the species examined except redwood have responded favorably in other studies (Powers and Jackson 1979; Carlson and Preisig 1981; Arnott and Burdett 1988; van den Driessche 1988), we conclude that interactions among fertilizer type, site, and climate limited the response to fertilization more than did the species used. When effective, fertilization provided an early pulse of increased growth that had little long-term effect on seedling growth trajectory.

Overall, mortality was high at all of the sites examined. The high mortality was generally more related to stochastic events than to the treatments applied. For example, at the Vernonia site a record rain year combined with harvesting disturbance resulted in the creation of several vernal pools across the study area. Seedlings planted in or near these areas were killed by long exposure to excessively wet conditions. At the Klickitat-PIPO site a large gopher population developed in years 2 and 3, and they killed several trees. The Arcata-SESE site was located on a relatively dry site for redwood and on a southern exposure that coupled with poor weed control in year 1 resulted in a large percentage of seedlings dying because of summer drought in year 1. At the Seaside-TSHE site, most of the mortality had occurred within the first month of planting suggesting problems with the nursery stock or in handling.

Only at the Drain-PSME and Arcata sites was mortality percentage influenced by any of the applied treatments. The Drain-PSME site was the most arid of the two Douglas-fir sites examined. This was especially true during the establishment year when the entire region experienced an unusually dry warm spring and summer. Weed control, especially the largest area treatments, likely provided greater levels of soil moisture allowing some seedlings at risk to survive. Mortality was greater in the fertilized plots at both the Drain-PSME and Arcata-SESE sites. Both these sites were in arid regions in the environmental range of conditions each species is planted in. Higher salt concentrations induced by fertilization coupled with arid conditions may have resulted in adverse osmotic effects and subsequently increased mortality (Brockley 1988).

Because of the high level of mortality across all the sites there was a concern that plots experiencing greater rates of mortality might also be experiencing reduced growth or that reduced stocking resulting from mortality may be influencing growth. These concerns were unwarranted, because plot growth and percent mortality tended to be poorly correlated. Only at the Drain-PSME site was a consistent growth and mortality correlation evident in all years of the study. However this is not surprising given that weed-control treatments at the Drain-PSME site influenced both growth and mortality.

Relative response to weed-control and fertilization treatments

At four of five sites, weed control resulted in more consistent and larger responses than from Woodace® fertilization. At Vernonia-PSME and Drain-PSME, the only sites to have both a weed-control and fertilization response, fertilization resulted in a considerably smaller increase in stem volume than did weed control. Our results suggest that if reforestation funds are limited, weed control will likely be a better silvicultural investment than fertilization with Woodace® briquettes.

Weed control generally results in greater or equal early conifer growth than fertilization in the few studies to evaluate both treatments simultaneously in the Pacific Northwest (Austin and Strand 1960; Roth and Newton 1996; Powers and Reynolds 1999). Austin and Strand (1960) reported a 33% increase in second-year Douglas-fir basal diameter with a urea formaldahyde and triple-super-phosphate fertilizer compared with an 80% increase resulting from weed control; the fertilizer response only occurred when weed control was applied. Broadcast urea fertilization did not increase Douglas-fir growth in the presence or absence of weed control, but growth increased with weed control (Roth and Newton 1996). Ponderosa pine response to fertilization was nearly the same as to weed control on a relatively moist site. On a moderately moist site the fertilization response was lessened relative to the weed control response and only was evident if weed control was applied (Powers and Reynolds 1999). However, they fertilized for several years in a row exponentially increasing the amount of fertilizer each year.

In other regions, the relative effects of fertilization and weed control have varied dramatically because of differing soils, environments, fertilizers used, application techniques, and crop species (Tiarks and Haywood 1986; Mason and Milne 1999; South et al. 1995; Swindel et al. 1988). In general, gains from weed control are found consistently and tend to be larger than from early fertilization. When gains from both treatments are observed independently, the responses tend to be additive.

Our results suggest that weed-control treatments influence seedling growth for a longer period than that of early fertilization treatments. The majority of gains achieved from fertilization were observed in year 1 or year 2. It was somewhat surprising that early gains in stem volume resulting from fer-

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tilization were not compounded over time because of the geometric nature of early volume growth similar to gains from weed control. The data suggests such a trend might exist but at this time could not be corroborated statistically. If these sites were followed further in time, such a trend might become more apparent. Other investigators (Carlson and Preisig 1981; van den Driessche 1988) have reported an increasing response to fertilization over the first 3–5 years, but time as a variable was not tested statistically by either.

The fertilizer briquettes used were designed to completely release within the first 18 months of growth, which most likely explains the short-term nature of the measured response. The weed-control treatments were repeated in year 2; in some cases, differences in cover were still evident into year 3, which helps to explain the longer term impact of weed control on growth. However, even after weed control no longer affected cover (year 4 at Vernonia-PSME and Klickitat-PIPO), the differences among weed-control treatments continued to increase. Several other studies have demonstrated a similar continued and increasing growth rate to early weed control (Hanson 1997; Stein 1995; Oliver 1990; Newton and Preest 1988; White and Newton 1990). In part, the increasing growth rate resulting from weed control is likely due to positive feedback of larger trees being able to capture an ever-increasing share of site resources and increasing their growth rate.

The herbicide used differed by site and may have slightly influenced the responses measured. Of the three different herbicides used, sulfometuron is the most likely to have had negative impacts on conifer growth. In other studies this herbicide has been shown to cause growth reductions of Douglas-fir and loblolly pine (Cole and Newton 1986; Barnes et al. 1990). However, both conifers also respond positively to the weed control realized from the weed-control treatments. It is interesting that the best growth occurred at the Vernonia site, which received two applications of the sulfometuron herbicide. If an equal level of weed control could have been achieved with another herbicide we might have seen a greater response to weed control at this site.

Soil moisture and response to fertilization

The three sites in which fertilizer responses occurred had the greatest mean annual precipitation, which highlights the importance of having adequate soil moisture for release and sorption of nutrients. Powers and Ferrell (1996) also found that annual precipitation increased the likelihood of a fertilizer response. Most studies in the Pacific Northwest that show positive seedling responses to fertilizer have been on sites that have naturally low vegetation cover, that have been burned, or that typically do not have extended dry periods (Powers and Jackson 1979; Carlson and Preisig 1981*a*, 1981*b*; Strothmann 1980; Atalla 1987; Arnott and Burdett 1988; van den Driessche 1988; Powers and Ferrell 1996). Where responses were poor or negative, either vegetation was not controlled or the fertilizer increased competition (Crouch and Radwan 1981; White and Newton 1990; Roth and Newton 1996). These findings strongly suggest that aggressive weed control is needed to obtain a positive fertilizer response on sites with extended soil moisture deficits.

Weed control has been shown to consistently increase soil moisture availability (Petersen et al. 1988) and subsequently in greater nutrient release and absorption (Nambiar and Sands 1993). We would, therefore, expect to also measure a subsequent increased response to fertilization with increased area of control. Surprisingly, gains were additive across all treatments at sites where a fertilizer response occurred. In the southeastern United States, similar additive responses to area of weed control and fertilization have occurred with loblolly and slash pines (Tiarks and Haywood 1986; Swindel et al. 1988). However, these sites do not experience the extended summer moisture stress common to sites in the Pacific Northwest. It is unclear whether there was no interaction between fertilization and weed control or our experimental procedure did not have the statistical power to identify such a small response. Using larger spot weed-control treatments may have resulted in a greater availability of soil moisture and thus greater potential to observe an interaction between fertilization and weed control. Rose et al. (1999) illustrated that growth was considerably less with a spot vegetation-control area of 3.3 m^2 than with a broadcast herbicide application on some western Oregon and Washington sites. They attributed this loss of growth potential to competition for both moisture and nutrients from weeds outside the weed-control areas.

Briquettes

The inherent properties of Woodace® briquettes may have limited the nutrient release and, thus, the growth response of conifers. The briquettes are very hard; they remain intact and do not honeycomb (dissolve) over the first years after planting. The briquettes are 3–4 cm in diameter and much larger than conventional slow-release fertilizers. Nutrients in the interior of briquettes may not release at the same rates as those nearer the surface, and smaller or broken briquettes may release nutrients more readily. In leachate studies in a container nursery, over 90% of the N was released in 1 year (Ingram and Yeager 1986). Ingram and Yeager (1986) postulated that increased irrigation rate increased the release of N from the briquettes and increased foliar N concentration of *Rhododendron* L. species. Surface area of the briquettes did not influence dissolution rates (Yeager and Ingram 1986). This further suggests that soil moisture is the most important factor limiting fertilization response on many sites.

Foliar nutrient concentrations

After 1 year, foliage concentration of P, K, Ca, Mg, and B dropped from nursery levels in the weed control and the fertilization treatments at all the sites. Nitrogen concentration dropped in the check treatments at all sites, but the drop was less in the larger areas of control at Vernonia-PSME, Drain-PSME, and Klickitat-PIPO. Early drop in foliage nutrient concentration from nursery levels was also observed by van den Driessche (1988) after outplanting from the nursery.

Such drops are not surprising. As seedlings burst bud and expand their new shoots, demand for additional nutrients is high. Yet bare-root seedlings often have fewer third-order roots than unlifted seedlings (Burdett 1990; Deans et al. 1990), which impairs water uptake, causes buildup of plant moisture stress, and retards new root growth (Rietveld 1989). Bare-root seedlings must translocate nutrients from existing tissues to new actively growing tissues to accommodate the high demand for nutrients in the first year (van den

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Driessche 1985). Consequently, first-year foliar nutrient levels drop.

Nitrogen concentration at the Drain-PSME and Klickitat-PIPO sites increased with area of weed control. This supports the findings of other investigators (Cole and Newton 1986; Brand and Janas 1988; Munson and Timmer 1995). Nitrogen is typically more mobile in soils than are P and K. Absorption of P and K is largely influenced by the absorptive area of plant roots, with root hairs playing a very important role in increasing absorptive area (Marschner 1995). Limited numbers of root hairs on bare-root stock soon after planting may have limited the ability of seedlings to absorb less mobile nutrients. By year 2, differences in N concentrations were not evident except at Arcata-SESE.

Boron was the only foliage nutrient tested to be consistently higher in fertilized treatments. Interestingly, this nutrient is not listed on the Woodace product label. The consistent increase in foliage B concentration is difficult to explain. It is possible that the fertilizer might have increased B availability by changing the soil pH in the root environment. Only at Drain-PSME were other nutrient concentrations affected by fertilization. Here N and Ca concentration increased while P concentration decreased. The decrease in P concentration appears to be due to dilution (Ulrich 1948) and the lack of continued soil availability. Boron concentrations continued to be greater even into year 2 at Vernonia-PSME and Klickitat-PIPO.

Obtaining consistent growth responses to seedling fertilization in the Pacific Northwest likely will depend on properly integrating many interdependent factors: fertilizer source, application rate, placement, stock-type, site preparation, and vegetation control (Brockley 1988). We attribute the lack of response we measured using Woodace briquette fertilization partly to briquette size, low soil moisture, and placement of the pellet. We continue to explore new approaches to seedling fertilization in combination with weed control because of the potential gains in plant growth.

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