Response of coastal Douglas-fir and competing vegetation to repeated and delayed weed control treatments during early plantation development

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Abstract: A key silvicultural decision in managing young conifer plantations is determining the number and timing of release treatments to control competing vegetation. Three coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantations were treated under eight alternative herbicide regimes during the first 5 years after planting to test treatment effects on vegetation dynamics and seedling growth. After termination of herbicide treatments, competing vegetation developed at a rate similar to that of check plots, reaching 40%–60% cover in the first growing season and approaching 100% by the third. Recovery of competing vegetation was slightly more rapid with greater number of previous releases. Annual volume growth of seedlings was negatively correlated with current cover of competing vegetation, but competitive effects from previous years were fully accounted for by initial tree size. Under 4 years of release, delaying treatment by 1 year reduced volume attained at the end of 5 years by about 15%. Plots receiving 5 consecutive years of weed control reached the 5 year volume of check plots in only 3.9 years, implying an age shift of 1.1 years. Increasing the number of operational release treatments significantly improved seedling growth in the short term, but long-term growth effects must be monitored to determine the economically optimal regime.

Résumé : Déterminer le nombre et le moment d’application des dégagements pour maîtriser la végétation compétitrice constitue une décision sylvicole cruciale pour l’aménagement de jeunes plantations de conifères. Trois plantations côtières de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) ont été traitées à l’aide de huit régimes d’herbicide différents pendant les cinq premières années après la plantation de façon à tester les effets des traitements sur la dynamique de la végétation et la croissance des semis. Après l’application des traitements d’herbicide, la végétation compétitrice s’est développée à un rythme similaire à celui des témoins, ce qui a permis à son couvert d’atteindre de 40 % à 60 % pendant la première saison de croissance et d’approcher 100 % lors de la troisième saison de croissance. La récupération de la végétation compétitrice a été légèrement plus rapide dans le cas des traitements comportant un grand nombre de dégagements antérieurs. La croissance annuelle en volume des semis était négativement corrélée au couvert de végétation compétitrice observé la même année, mais les effets de la compétition des années antérieures étaient pleinement expliqués par la taille initiale des semis. Pour le traitement comportant quatre dégagements annuels, le fait de retarder le traitement d’une année a réduit d’environ 15 % le volume atteint à la fin d’une période de 5 ans. Les parcelles ayant reçu cinq dégagements annuels consécutifs ont atteint le volume quinquennal des témoins en seulement 3,9 ans, ce qui correspond à une réduction du temps requis de 1,1 an. L’augmentation du nombre de traitements de dégagement a significativement amélioré la croissance des semis à court terme, mais on doit suivre les effets à long terme sur la croissance des semis pour déterminer le régime optimal du point de vue économique.

[Traduit par la Rédaction]

Introduction

Control of competing vegetation is often important for successful plantation establishment and can significantly increase early tree growth in many forest types (Cole and Newton 1987; Newton and Preest 1988; Monleon et al. 1999; Nilsson and Allen 2003; Rose et al. 2006). Rapid early growth of a tree crop helps landowners achieve desired yields in a shorter time period (Mason and Milne 1999; Wagner et al. 2005), reduces the period of susceptibility to browse damage (O’Dea et al. 2000), and accelerates “green up”, the “free to grow” condition required by many forest practice rules before adjacent units can be harvested (Rose and Haase 2006). Control of competing vegetation with chemical herbicides has become a standard operation on forestland managed for timber production in the Pacific Northwest. During the last 30 years, the management objective on these lands has shifted from maximization of yield to maximization of return on investment (Talbert and Marshall 2005). Competing vegetation is aggressively treated in pursuit of this latter objective, and chemical control is the method preferred by most landowners (~60%; Briggs

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2007). Since 2005 chemical site preparation has been applied on approximately 65% of industrial forestland replanted to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and another 3% per year received some type of release treatment from competing vegetation over the same period (Briggs 2007).

Effective chemical control of competing vegetation requires selection of the most appropriate herbicide and rate of application. However, foresters also must decide whether conditions warrant one versus multiple years of release, and whether a delay of 1 or 2 years will have a lasting adverse effect on plantation growth. The critical period (CP) concept of weed control, as initially applied to agricultural crops (Nieto et al. 1968), suggests that weed control will maximize the yield of an annual crop only if implemented during a specific period between crop-species emergence and growth-cycle completion. Outside the CP, weed control will have a minimal benefit to crop yield. Application of the CP concept to perennial forest crops is more complicated, primarily because the efficacy of competing vegetation control depends both on timing within a growing season and on the specific growing seasons selected for treatment. In addition, true “weed-free” conditions are seldom attained for an entire growing season or for several successive years in forest plantations, even under tightly controlled experimental conditions. Operational control of competing vegetation in conifer plantations is generally limited to spring and fall to avoid the period of active shoot growth of the crop species. Mid-season treatments generally involve limited manual or chemical treatments directed at stems or clumps of woody species, or spot spraying between tree seedlings; hence, weed control is typically less than complete. Identification of the CP by creating “weed-free” and “weed-infested” periods of varying length is further complicated by differences in germination date, growth phenology, and relative dominance between herbaceous and woody competition over the course of early stand development (Harrington et al. 1995; Stein 1995). Even for an annual crop species, the apparent CP for maximizing yield depends on competing plant species, crop and weed density, site factors, and annual and seasonal fluctuations in growing conditions (Zimdahl 1988). Variability attributable to these factors is potentially even greater for perennial forest crops and therefore has made necessary some modification of the original CP concept. The most significant modification has been the change from a weekly or daily treatment resolution in agriculture to an annual resolution in silviculture. Specifically, researchers have applied the CP concept to identify thresholds in the number of years of competing vegetation control that are required to establish and maximize growth of commercial timber species, including various eucalypts (Adams et al. 2003) and northern conifers (Wagner et al. 1999; Wagner and Robinson 2006). In four of the five species tested in one experiment, yield was maximized by starting control of competing vegetation during the year of planting, with the required number of years of subsequent treatment dependent on species: 2 years for eucalypts (Adams et al. 2003) and jack pine (*Pinus banksiana* Lamb.), 3 years for red pine (*Pinus resinosa* Ait.), and 5 years or more for eastern white pine (*Pinus strobus* L.) and black spruce (*Picea mariana* (Mill.) BSP) (Wagner et al. 1999; Wagner and Robinson 2006).

The benefits of competing vegetation control to wood production have been expressed both as yield gain at a given rotation length and as reduction in rotation length to attain a given yield, the latter frequently referred to as “age shift” or “time gain” (Pienaar and Rheney 1995; Mason and Milne 1999; Miller et al. 2003; South et al. 2005; Wagner et al. 2005). Adequate characterization of biological response surfaces, with respect to both competing vegetation and crop growth, is critical for identifying control regimes that are optimal from both an economic and environmental perspective. Timber producers in the Pacific Northwest now aim for shorter rotations to maintain competitiveness in an increasingly global wood market, particularly given the currently low premium for large high-quality logs (Murphy et al. 2005). Previous estimates of time gain attainable with competing vegetation control have varied from 2 to 5 years at the end of the rotation in loblolly pine (*Pinus taeda* L.), depending on the intensity of control and the presence of competing hardwood trees (Lauer et al. 1993; South et al. 2005). Age shifts of similar magnitude are likely for Douglas-fir.

A critical period threshold (CPT) study was established in western Oregon by the Vegetation Management Research Cooperative (Oregon State University) in 2000 and 2001 (Rosner and Rose 2006). To our knowledge, only one other silvicultural study (Wagner and Robinson 2006) has tested the CP concept at an annual resolution by measuring conifer response to alternative weed control regimes over the first 5 years of plantation development. This paper reports results for Douglas-fir and implications for the CP of competing vegetation control. The goal was to test the CP concept at an annual resolution by assessing the development of competing vegetation under alternative treatment regimes, as well as the response of crop trees to these same regimes. Specific objectives included (1) developing a model for predicting competing vegetation development under alternative control regimes; (2) developing a model for predicting annual tree growth as a function of initial seedling size, cumulative effects of competing vegetation, and current level of competing vegetation; (3) testing the hypothesis that prior effects of competing vegetation on crop tree growth potential are fully represented by tree size at a given age; (4) testing the null hypothesis that tree volume at the end of 5 years depends only on the number of years of treatment and not on the specific regime (i.e., no CP effect); (5) estimating the current age shift under each competing vegetation control treatment; and (6) testing the null hypothesis that competing vegetation control does not affect height growth and, by implication, estimates of site index.

Methods

Study design

The study was designed as a randomized complete-block experiment with eight treatments. Each treatment was implemented on four blocks at each of three study sites. Although blocks of other species were also established, this analysis focuses only on the four Douglas-fir blocks at each site. Treatment units comprised six rows of six Styro-15 seedlings planted on a 3 m (10-ft) spacing.

Sites

The three study sites were located on the north coast (Seaside), in the central Coast Range (Summit), and in the Cascade foothills (Sweet Home) of Oregon. The Seaside site was established in winter 2001 and is approximately 8 km from the Pacific coast (45.94°N, 123.89°W). Elevation and annual precipitation average 200 m and 215 cm, respectively. The Summit site was established in January 2000 and is approximately 40 km from the coast (44.62°N, 123.57°W). Elevation averages 250 m, and annual precipitation averages 215 cm. The Sweet Home site was established in winter 2001 and is approximately 110 km from the coast (44.48°N, 122.73°W). Elevation and annual precipitation average 200 m and 125 cm, respectively. At all three sites most of the precipitation falls as rain from October to April.

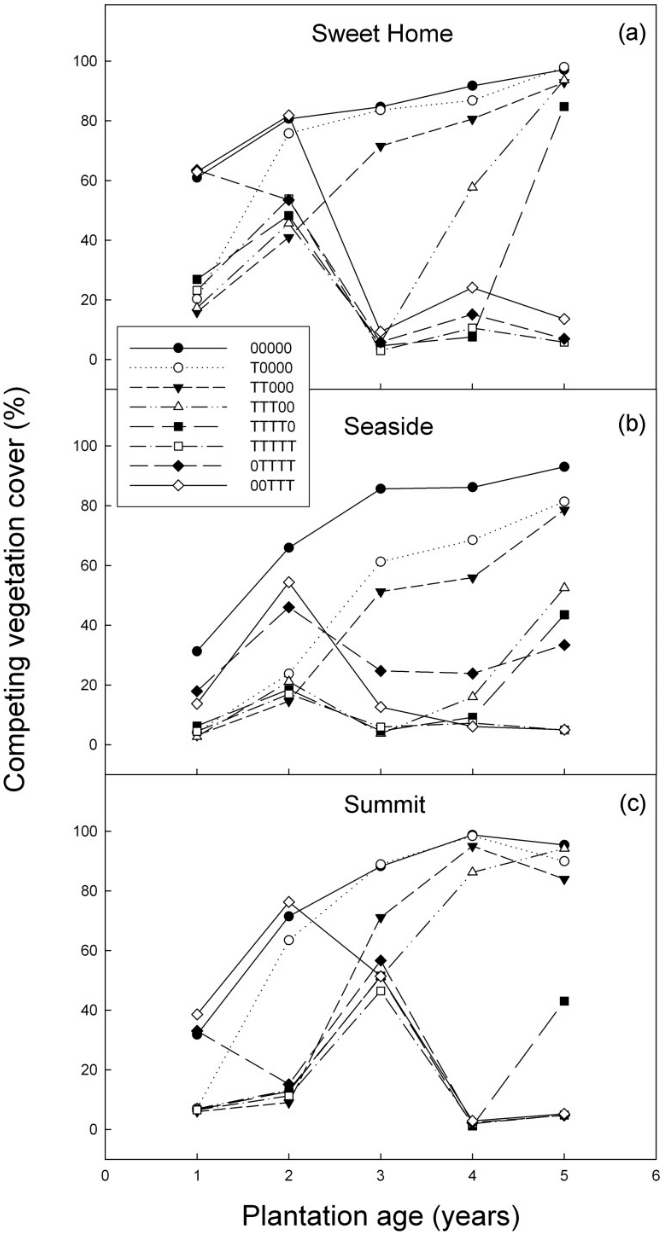
Logging slash was piled by excavator away from the treatment units. While piling slash, the excavator also pulled existing shrub clumps. The Summit and Sweet Home sites were subsoiled after completion of excavator piling to ameliorate any compaction that may have been caused by harvesting operations. A directed herbicide treatment (imazapyr, 2.5%) was applied in any treatment unit where elimination of sprouting hardwoods, primarily bigleaf maple (*Acer macrophyllum* Pursh), was deemed necessary (including check plots that received no subsequent competing vegetation control).

Treatments

The eight competing vegetation regimes were defined by the number and timing of herbicide treatments (T) during the first 5 years following planting. The regimes can be lumped into three general types: check treatment (no competing vegetation control beyond initial treatment of shrub and hardwood clumps; designated as OOOOO), 1 to 5 consecutive years of release immediately following planting (designated as TOOOO, TTOOO, TTTOO, TTTTO, and TTTTT), and 1 or 2 years of delay followed by successive years of release through year 5 (designated as OTTTT and OOTTT).

The goal of a treatment (T) in any given year was to maintain competing vegetation below 25% cover during the entire growing season. If greater than 25% cover remained after treatment or was expected to develop later in the season, additional treatments were applied. A premature and ineffective spring treatment in 2002 (year 2 at Sweet Home and Seaside, year 3 at Summit) reduced herbicide efficacy and allowed competing vegetation cover to reach 50% on some treated plots (Fig. 1). All plots scheduled for competing vegetation control in the first year after planting were chemically site prepared with a fall broadcast application of sulfometuron (0.15 L/ha), metsulfuron (0.04 L/ha), and glyphosate (4.68 L/ha). Annual spring release from competing vegetation was achieved by application of atrazine (4.5–4.9 kg/ha) and clopyralid (0.58–0.73 L/ha). If cover exceeded the designated 25% threshold during the growing season, glyphosate (1.5%–2.0%) was applied in late spring or early summer. Occasionally, treatments were applied in the fall on plots designated for treatment the following year if those plots contained high cover of species unlikely to be controlled by spring applications. Fall release from competing vegetation was achieved by broadcast applications of glyphosate (1.5%–2.0%) and occasionally clopyralid (0.5%) or atrazine (4.5 kg/ha), with rates dependent on the abundance of target species. Each spring of competing vegetation control, regardless of the need for additional fall or summer release, will hereafter be referred to as a single release.

Fig. 1. Percent cover of competing vegetation by year and treatment in the critical period threshold study: (*a*) Sweet Home, (*b*) Seaside, and (*c*) Summit. Treatments were as follows: check treatment (no competing vegetation control beyond initial treatment of shrub and hardwood clumps; designated as OOOOO); 1 to 5 consecutive years of release immediately following planting (designated as TOOOO, TTOOO, TTTOO, TTTTO, and TTTTT); and 1 or 2 years of delay followed by successive years of release through year 5 (designated as OTTTT and OOTTT).



Measurements

Initial basal diameter at 15 cm above groundline (D15) and total height were measured in the field prior to the first growing season. Each subsequent fall, tree measurements included seedling height and D15, as well as diameter at breast height (DBH) if the tree reached a height of 1.37 m. Two crown radii were measured on each tree starting in 2004 (fifth year of growth at the Summit site and fourth year of growth at Sweet Home and Seaside). Total percent cover of all vegetation and separate percent cover of each plant species was estimated in late summer on six 1 m radius subplots per treatment unit. Although the summed cover of each plant species exceeded 100% in some cases, the estimate of total percent cover was based on total ground coverage of competing vegetation and therefore could not exceed 100%. Initially these subplots were tree centered, but in 2003 they were moved northwest by 2.16 m to a point equidistant from four surrounding plot trees.

Analysis

Competing vegetation cover

Visual estimates were averaged across the six subplots within a treatment unit to estimate total competing vegetation cover, TCOV (%). Temporal development of total cover generally depended on both the time since last herbicide application (YSH) and the number of prior release treatments (NH), as represented in the following nonlinear model:

$$[1] \qquad \mathrm{TCOV} = \alpha_0 + \alpha_1[1 - \exp(-(\alpha_2 + \alpha_3\mathrm{NH})\mathrm{YSH})] + \varepsilon_1$$

where the α_i's are parameters to be estimated from the data, and ε_1 is a random error term with $\varepsilon_1 \sim \mathrm{N}(0, \sigma_1^2)$. An expanded model was explored by introducing site as a fixed effect on each α_i and allowing α_0 to differ for 2002, the year of reduced herbicide efficacy. Random effects of block within site on parameters α_0 and α_3 were also tested by fitting nonlinear mixed-effects models with SAS PROC NLMIXED (SAS Institute Inc. 1996).

Tree growth

Volumes of trees shorter than 1.37 m were calculated as the volume of a cone with basal diameter equal to D15. For taller trees, the volume of the section below 1.37 m was calculated with Smalian's formula (Husch et al. 1982; pp. 98–101) based on D15 and DBH. The volume of the top section (above 1.37 m) was computed as the volume of a cone with basal diameter equal to DBH. Annual volume growth rates for each tree were computed as successive differences in total volumes.

Individual-tree volume growth was averaged for each treatment unit and each 1 year growth period. To meet the second study objective, volume growth for any given year was expressed as a function of initial tree size (V_0), the amount of prior vegetation competition CCOV in %, and TCOV. The basic model was

$$[2] \qquad \ln(\Delta V) = \tau_i + \pi_j + \tau\pi_{ij} + \beta_1\mathrm{CCOV} + \beta_2 \ln(V_0) + \beta_3\mathrm{TCOV} + \beta_4 \ln(V_0)\mathrm{TCOV} + \varepsilon_2$$

where ΔV is volume growth (dm^3), τ_i is the site effect, π_j is the year effect, the β_k's are parameters to be estimated from the data, and ε_2 is a random error term. Because the data represented repeated measures on each experimental unit, the distribution of ε_2 was modeled with an autoregressive covariance structure, and the model was fitted with SAS PROC MIXED (SAS Institute Inc. 1996). Variables tested as surrogates for prior competition (CCOV) included cumulative cover over all previous years, cumulative cover in the first 2 years, total cover in the prior year, and total cover in the 2 prior years.

The third objective was addressed by testing whether β_1 in eq. 2 was significantly different from zero at $\alpha = 0.05$. If initial tree size (V_0) integrated cumulative competing vegetation effects, the model should reduce to

$$[3] \qquad \ln(\Delta V) = \tau_i + \pi_j + \tau\pi_{ij} + \gamma_1 \ln(V_0) + \gamma_2\mathrm{TCOV} + \gamma_3 \ln(V_0)\mathrm{TCOV} + \varepsilon_3$$

where the γ_k's are parameters to be estimated from the data, and ε_3 is an error term following the same autoregressive covariance structure as that described for eq. 2.

If treatments for controlling competing vegetation in Douglas-fir plantations lack a CPT over the first 5 years of plantation development, then tree growth should respond only to the number of release treatments and not to the specific years of treatment. In the case of the Oregon CPT study, this amounts to testing the effects of a 1 or 2 year delay in treatment. The following model was fitted to the data to test whether treatment delay had a significant effect on tree growth (fourth objective):

$$[4] \qquad V_5 = \tau_i + \delta_0 + \delta_1 t_1 + \delta_2 t_2 + \delta_3 t_3 + \delta_4 t_4 + \delta_5 t_5 + \delta_6 D t_3 + \delta_7 D t_4 + \varepsilon_4$$

where V_5 is average tree volume (dm^3) in year 5, τ_i is the site effect, t_k is 1 if the plot received k years of release (with or without delay) and 0 otherwise, D is 1 if treatment was delayed for 1 or 2 years (followed by 4 or 3 years of vegetation control, respectively) and 0 otherwise, and ε_4 is a random error term with $\varepsilon_4 \sim N(0, \sigma_4^2)$. A histogram was also constructed to depict differences in the least squares means from eq. 4 among all eight treatment regimes (Neter et al. 1990; p. 244).

Age shift was defined as the reduction in time required to produce the same 5 year stem volume as that of the check plots receiving no vegetation control (objective 5). Age shifts were estimated by first modeling plot volume as a function of site, plantation age (A_p), and treatment regime, and then solving for the age required for a given treatment to reach the average volume of the check plots:

$$[5] \qquad \ln(V_\mathrm{plot}) = \lambda_0 + \lambda_1\mathrm{SH} + \lambda_2\mathrm{SS} + \lambda_3 \ln(A_\mathrm{p}) + \lambda_4 I_\mathrm{TOOOO} + \lambda_5 I_\mathrm{TTOOO} + \lambda_6 I_\mathrm{TTTOO} + \lambda_7 I_\mathrm{TTTTO} + \lambda_8 I_\mathrm{TTTTT} + \lambda_9 I_\mathrm{TOOOO} \ln(A_\mathrm{p}) + \lambda_{10} I_\mathrm{TTOOO} \ln(A_\mathrm{p}) + \lambda_{11} I_\mathrm{TTTOO} \ln(A_\mathrm{p}) + \lambda_{12} I_\mathrm{TTTTO} \ln(A_\mathrm{p}) + \lambda_{13} I_\mathrm{TTTTT} \ln(A_\mathrm{p}) + \varepsilon_5$$

Table 1. Mean percent cover of plant species in the western Oregon critical period threshold study by site and treatment regime, 5 years after plantation establishment.

	Summit			Sweet Home			Seaside		
Species	OOOOO	TTTOO	TTTTT	OOOOO	TTTOO	TTTTT	OOOOO	TTTOO	TTTTT
Alnus rubra							27.3		
Chrysanthemum leucanthemum				17.0		0.8			
Cirsium arvense						0.8			
Crepis setosa					8.0				
Crepis capillaris		6.9							
Digitalis purpurea			1.2						
Epilobium angustifolium				9.0					
Equisetum arvense									1.8
Galium triflorum			0.8						
Holcus lanatus	9.7	10.4	0.9	9.6	13.8	0.8	15.6	13.1	0.6
Hypochaeris radicata		39.0	0.8	10.3	50.2	1.4		23.5	2.6
Lotus crassifolius	10.2								
Picea sitchensis									1.3
Poaceae								4.4	
Pteridium aquilinum		10.2			6.2				
Rumex acetosella								4.3	
Rubus laciniatus						1.0		2.3	0.7
Rubus parviflorus	7.9								
Rubus procerus	8.2								
Rubus spectabilis							31.4		
Rubus ursinus	35.0	36.9	1.8	39.2	6.7				
Sambucus racemosa							13.3		
Tsuga heterophylla							24.1		

Note: Treatment codes are described in Fig. 1 caption.

where V_{plot} is plot volume (dm^3/plot) at A_{p}, I_m is 1 for treatment regime m and 0 otherwise, SH is 1 for Sweet Home and 0 otherwise, SS is 1 for Seaside and 0 otherwise, ε_5 is a random error term with $\varepsilon_5 \sim N(0, \sigma_5^2)$, and A_{p} is as defined above.

Application of site index for plantation silviculture assumes little or no effect of competition on height growth of trees. This assumption was tested by comparing average tree height in year 5 among the different competing vegetation treatments (objective 5) with a protected least significant difference approach (Steel and Torrie 1980; pp. 173–177).

Results

Competing vegetation on the check plots (OOOOO) was dominated by trailing blackberry (*Rubus ursinus* Cham. & Schldtl.) at Summit and Sweet Home (35%–40% cover) and by red alder (*Alnus rubra* Bong.), salmonberry (*Rubus spectabilis* Pursh.), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) at Seaside (each over 24% cover; Table 1). Introduced composites oxeye daisy (*Chrysanthemum leucanthemum* L.) and hairy cat's ear (*Hypochaeris radicata* L.) also formed significant cover (>10%) on the check plots at Sweet Home, as did big deervetch (*Lotus crassifolius* (Benth.) Greene) at Summit (10%) and common velvetgrass (*Holcus lanatus* L.) at all three sites (10%–15%; Table 1). Total cover was very low in year 5 on the TTTTT plots but generally did include these common species. *Hypochaeris radicata* cover was conspicuously higher (24%–50% cover) in year 5 on TTT00 plots at all three sites.

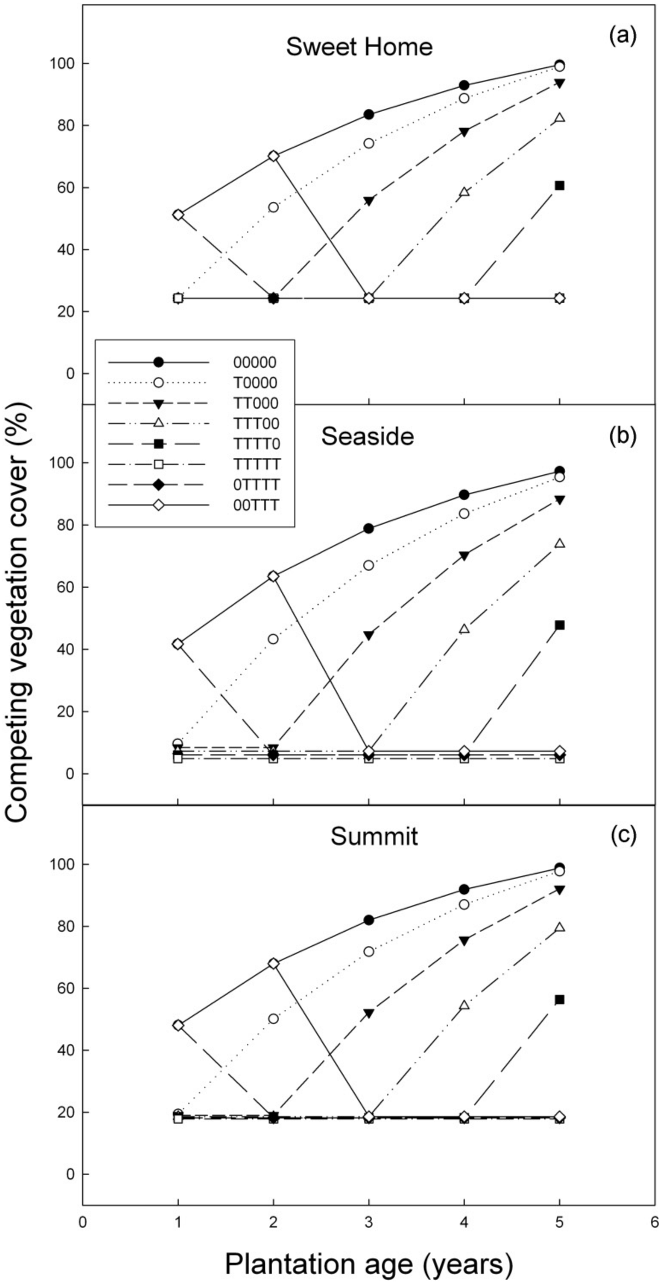
Vegetation cover

Competing vegetation increased rapidly on the check plots after harvest and hardwood removal, climbing to near 100% by the third year (Fig. 1). On average, TCOV reached approximately 40% on the untreated check plots during the first growing season (Fig. 1). In contrast, any spring release treatment kept TCOV at about 10% during the subsequent growing season. With no further treatment, however, the rebound in TCOV was strong in the next growing season, averaging ~60% regardless of the number of previous treatments. In absence of treatment, TCOV continued to increase at a decreasing rate, approaching 100% asymptotically. Spring release after a 1 or 2 year delay generally caused an immediate reduction in TCOV, although this response was damped in 2002 because of reduced herbicide efficacy. The general pattern in competing vegetation development was consistent across all three sites, although competing vegetation was somewhat less vigorous at Seaside than at the other two sites.

The final model for describing development of vegetation cover reflected site differences and the relatively high cover of competing vegetation on treated plots in 2002:

$$[6] \quad \text{TCOV} = (\zeta_0 + \zeta_1 I_{2002} + \upsilon) + [100 - (\zeta_0 + \zeta_1 I_{2002} + \upsilon)][1 - \exp(-(\zeta_2 + \zeta_3 \text{SS} + \zeta_4 \text{NH} + \zeta_5 \text{SS} \times \text{NH})\text{YSH})] + \varepsilon_6$$

Fig. 2. Predicted cover of competing vegetation by year and treatment in the critical period threshold study: (*a*) Sweet Home, (*b*) Seaside, and (*c*) Summit (estimated from eq. 6). Treatment codes are described in Fig. 1 caption.



where I_{2002} is 1 for observations in 2002 and 0 otherwise, ζ_i's are parameters to be estimated from the data, υ is a random block (within site) effect with $\upsilon \sim N(0, \sigma_{\upsilon}^2)$, ε_6 is a random error term with $\varepsilon_6 \sim N(0, \sigma_6^2)$, and all other variables are as defined above.

The number of treatment years (NH) and the time since the most recent treatment (YSH) were the primary drivers of competing vegetation development. On average, herbicide treatment reduced cover to 9% at all sites, except in 2002 (Fig. 2; Table 2). At the end of the first, second, and third growing season after the last scheduled application, vegetation cover at Seaside averaged 38%, 58%, and 70%, respectively, and at Sweet Home and Summit, it averaged 65%, 85%, and 92%, respectively (Fig. 2). As the number of release treatments increased, the rebound in weed cover in each subsequent year increased slightly, with vegetation cover in year 5 of the TTTTO treatment exceeding that in year 2 of the TOOOO treatment by 7%.

Table 2. Parameter estimates for the model describing dynamics of competing vegetation under different number and timing of release treatments in the western Oregon critical period threshold study (eq. 6).

Parameter	Estimate	SE
ζ_0	9.5287	2.0795
ζ_1	29.5989	1.8594
ζ_2	0.5872	0.0373
ζ_3	–0.2319	0.0457
ζ_4	0.1498	0.0293
ζ_5	–0.1383	0.0338
σ_{υ}^2	41.8281	21.0851
σ_6^2	177.10	11.6194

Table 3. Parameter estimates for the model describing annual tree volume growth as a function of initial tree size and current level of competing vegetation in the western Oregon critical period threshold study (eq. 3).

Variable	Estimate	SE
γ_0	4.73000	0.05776
γ_1	0.50050	0.03663
γ_2	–0.00530	0.00054
γ_3	–0.00109	0.00020

Volume growth

None of the surrogates for cumulative cover of competing vegetation explained any additional variation in annual tree growth beyond the cumulative effect represented by tree size at the beginning of any given year. After accounting for site, measurement period, and their interaction, volume growth was positively correlated with initial volume and negatively correlated with total cover of competing vegetation (Table 3). The significant negative interaction between initial volume and vegetation cover reflected the declining effect of increasing competition on trees of greater initial size (Fig. 3).

Delay treatments

The effect of delaying herbicide treatment differed by the number of releases; however, the number of releases differed somewhat from targets, so a site by treatment interaction was evident. The planned contrasts suggested that a 2 year delay under 3 years of herbicide treatment (OOTTT vs. TTTOO) had no significant effect on cumulative volume growth at year 5 (p = 0.635; Fig. 4; Table 4). However, the herbicide treatment in 2002 was not effective at Summit (year 3), partially effective at Sweet Home (year 2), and largely effective at Seaside (year 2). When sites were ana-

Fig. 3. Effect of competing vegetation cover on the growth of Douglas-fir seedlings of varying initial size in the western Oregon critical period threshold study (estimated from eq. 2).

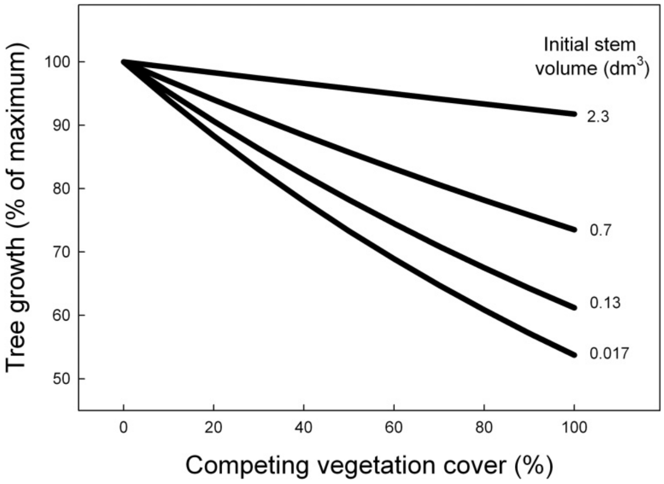
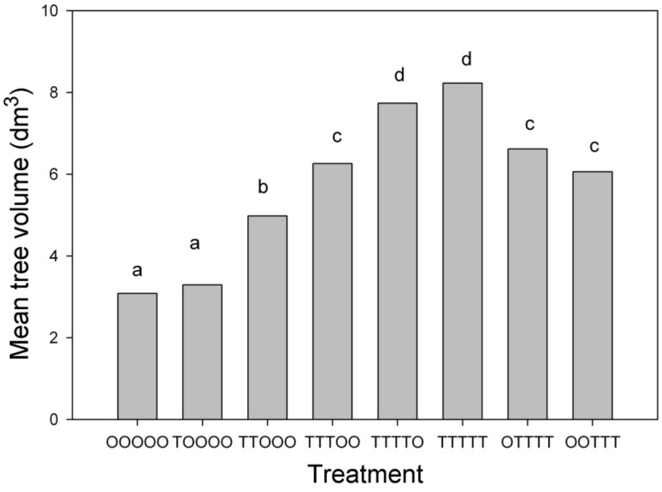


Fig. 4. Mean tree volume at year 5 for each treatment in the western Oregon critical period threshold study. Bars with the same letters are not significantly different at $\alpha = 0.05$. Treatment codes are described in Fig. 1 caption.



lyzed separately, the nominal 2 year delay resulted in significantly less volume at Sweet Home ($p = 0.0213$), but not at Summit ($p = 0.275$) or Seaside ($p = 0.689$). Under 4 years of release, all experimental units received treatment in 2002 (TTTTO or OTTTT), so contrasts were not dependent on site. In this case the 1 year delay resulted in 15% less tree volume at the end of the fifth growing season ($p = 0.009$).

Age shift

Equation 5 explained approximately 96% of the variation in the logarithm of standing volume (mean square error = 0.101; Table 5). Implied age shift reached approximately 1.1 years under the TTTTO and TTTTT treatments (Fig. 5). For the limited time covered by this analysis (5 years), age shifts appeared to persist after termination of treatments. Age shift generally increased with increasing number of release treatments, but a surprisingly small gain was observed for the treatment with one initial release (TOOOO), and a

Table 4. Parameter estimates for the model describing 5 year plot volume as a function of the number of release treatments and the delay in treatment for the western Oregon critical period threshold study (eq. 4).

Variable	Estimate	SE
δ_0	1.8902	0.4547
δ_1	0.2118	0.4173
δ_2	1.8953	0.4173
δ_3	3.1759	0.4173
δ_4	4.6555	0.4173
δ_5	5.1433	0.4173
δ_6	–0.1988	0.4173
δ_7	–1.1240	0.4173

Table 5. Parameter estimates for the model describing plot volume over time for each of the eight treatment regimes in the western Oregon critical period threshold study (eq. 5).

Variable	Estimate	SE
λ_0	–0.20516	0.14868
λ_1	–0.03359	0.04417
λ_2	0.49401	0.04417
λ_3	3.95962	0.10917
λ_4	0.034909	0.20420
λ_5	1.10214	0.20420
λ_6	1.08414	0.20420
λ_7	0.94405	0.20420
λ_8	0.74353	0.20420
λ_9	–0.16208	0.15378
λ_{10}	–0.31897	0.15378
λ_{11}	–0.18396	0.15378
λ_{12}	0.07029	0.15378
λ_{13}	0.19999	0.15378

Fig. 5. Age shift, or reduction in time by which each treatment produces the same average tree volume as check plots (competing vegetation control) at age 5 years (estimated from eq. 3). Treatment codes are described in Fig. 1 caption.

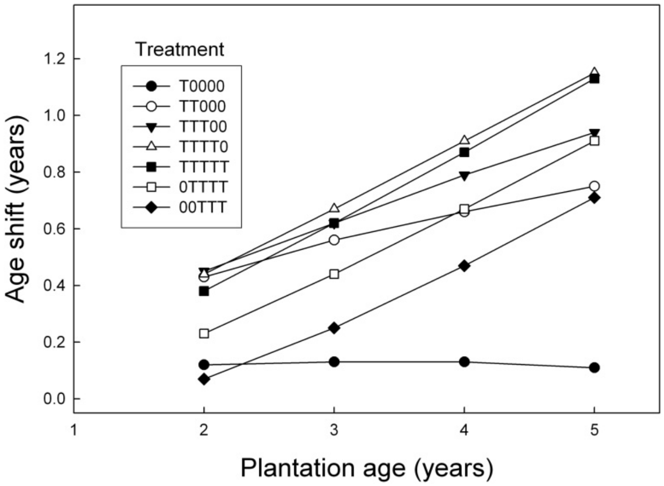
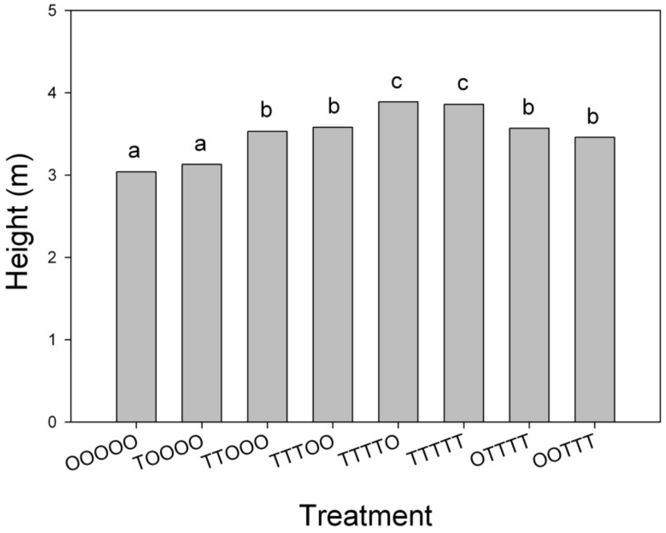


Fig. 6. Mean tree height at year 5 for each treatment in the western Oregon critical period threshold study. Bars with the same letters are not significantly different at $\alpha = 0.05$. Treatment codes are described in Fig. 1 caption.



surprisingly large gain was observed for the treatment with 2 years of initial release (TTOOO; Fig. 5).

Average height

The most intensive treatment regimes boosted average height by 0.85 m over that of the check plots by the end of the fifth growing season (Fig. 6). This acceleration in height growth represented a 28% increase, underscoring the limits of height growth as an index of inherent site productivity in absence of adjustment for past management history.

Discussion

Trends in total vegetation cover

Visual estimates of cover have been as effective as more complex measures of competing vegetation for predicting impacts on the growth of conifer seedlings (Coates 1987; Wagner and Radosevich 1991, 1998; Ter-Mikaelian et al. 1999; Bell et al. 2000). The generality of this result may not hold under dramatic differences in resource use efficiency among competing species, but within a site it simplifies field assessment of competition and allows prediction of crop-tree response to treatments with known or predictable effects on competing vegetation cover.

Subplots for estimating cover of competing vegetation were moved from a tree-centered position prior to 2003 (fourth growing season at Summit and third at Sweet Home and Seaside), because crown expansion of planted trees began to influence cover of the underlying ground vegetation. No evidence could be found in the data that this shift in subplot location caused an artificial increase in estimated vegetation cover. Likewise, comparisons of cover estimates in year 3 between Douglas-fir blocks and adjacent blocks with much smaller western redcedar (*Thuja plicata* Donn ex D. Don) seedlings indicated no significant differences in competing vegetation cover for a given treatment. Growth of western redcedar is slow relative to that of Douglas-fir in its juvenile stage (Reukema and Smith 1987), and field observations confirmed lack of influence on ground vegetation even at year 5 for this species. In short, differences in average vegetation cover among treatments reflected direct treatment effects on competing species. Indirect treatment effects from suppression of competing vegetation under planted trees were not measured but are tightly coupled with the initial tree size effect on tree growth.

Total percent cover was reduced to just under 10% by the herbicide treatments in the Oregon CPT study but recovered rapidly after herbicide applications ended. On untreated plots, vegetation cover averaged 47% during the first year after treatment termination and exceeded 90% by the fourth growing season (Fig. 1). Regardless of treatment regime, the pattern of recovery in competing vegetation was largely dictated by the number of years since the last release treatment and the number of previous releases. Competing vegetation on treated plots developed at a rate very similar to that on the check plots but increased slightly with the number of previous herbicide applications. By the third year of treatment at the Sweet Home site, repeated herbicide treatment had diminished the seed rain and depleted propagules in the seed and bud banks (Chen 2004). Although species richness of both native and exotic plants was reduced, herbicide application had greater impact on native species (Chen 2004), perhaps facilitating colonization by more aggressive exotic species with a strong R-selection (competitive-ruderal) strategy (Grime 1979; pp. 39–45).

Competing vegetation developed at slightly different rates among sites, with Seaside significantly slower than the other two sites. The number of plant species at the Seaside site was also lower than that at the Summit and Sweet Home sites (Chen 2004), perhaps because of limited local seed sources. The Seaside blocks were surrounded by dense Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and western hemlock stands with a relatively depauperate understory. Dense stands of Sitka spruce and western hemlock can shade out ground vegetation almost completely after crown closure (Alaback 1982), seriously reducing potential seed sources for recolonization of harvested sites. Similarly, little open range or farmland exists in this part of the Oregon Coast Range, further reducing the availability of seed or vegetative propagules for site colonization. In contrast, the Sweet Home and Summit sites are located in proximity to farmland and are surrounded by Douglas-fir stands of varying ages with relatively rich understories (Chen 2004).

The level of vegetation cover observed on treated plots in 2002 (age 3 at Summit and age 2 at Sweet Home and Seaside) corresponded to the year in which a premature spring release treatment reduced herbicide efficacy, probably due both to weed dormancy and continued spring precipitation. Precipitation has been shown to lessen herbicide efficacy in other studies (e.g., Nilsson and Karlsson 1987). Monthly precipitation in the vicinity of Corvallis for March of 2002 was about 7.6 cm (38%) higher than the 1971–2000 average, but for April through August the monthly precipitation was 1.3 to 3.8 cm lower (see www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?orcowb). Excluding the 2002 results, cover under the TTTTT treatment averaged 10.6%, 5.6%, and 6.2% over all 5 years at Sweet Home, Seaside, and Summit, respectively. By accounting for a fixed effect of the year 2002, average cover during any growing season following a spring release converged on 10%, regardless of site and treatment regime. Because the objective of release treatments in the CPT study was to limit competing vegetation to no more than 25% cover, multiple treatments per year were sometimes necessary. Operational treatments are typically less intensive because of financial and logistical constraints, so they may not necessarily keep vegetation cover below the target specified in this experiment. In this case, 10% may underestimate vegetation recovery following operational release, necessitating calibration of some model parameters, particularly ζ_0 in eq. 6.

Effect of cover on volume growth

Douglas-fir volume growth declined with increasing levels of competing vegetation in the current growing season, as previously reported in this study (Rosner and Rose 2006) and in many others (Coates 1987; Wagner and Radosevich 1991, 1998; Ter-Mikaelian et al. 1999; Bell et al. 2000). Variation in the intensity of previous competition imposes additional variability in volume growth potential of the tree in subsequent years; however, these effects were well accounted for by initial tree size in this and other studies of young Douglas-fir (Monleon et al. 1999; Harrington and Tappeiner 1991; Harrington et al. 1995). The declining negative impact of competing vegetation on seedling growth with increasing tree size (Fig. 3) was also consistent with other research on Douglas-fir (Wagner and Radosevich 1991, 1998). As young trees grow larger and expand their crowns they become better able to acquire resources at the expense of subordinate vegetation, causing suppression of herbs and low shrubs. The prevalence of one-sided or top-down competition in older forest stands is well documented (Kenkel 1988; Kikuzawa 1999; Ogawa and Hagihara 2003) and is strongly represented in individual-tree growth models (Hann and Ritchie 1988; Wykoff 1990; Pacala et al. 1993). Likewise, size-asymmetric competition is recognized as a strong influence on size-class structure of plant populations in general (Weiner and Whigham 1988; Schwinning and Weiner 1998). By year 5 at the Summit site, crown projection areas in the TTTTT treatments were nearly double those of the check plots. Measurements from year 8 in the Oregon CPT study indicate that significant crown overlap has occurred within the plots receiving 4 or 5 years of treatment and in the delayed treatment receiving three releases (E. Dinger, personal communication). Starting in 2002, vegetation cover was estimated at the point of least influence from potentially overlapping crowns; i.e., trees were planted on a grid, crown projection areas were roughly circular, and subplot centers were equidistant from measured trees. The growth impact of competing vegetation therefore diminished as trees increased in size because competing vegetation was eliminated from the central part of the tree's crown projection, and the remaining vegetation was increasingly suppressed.

Two different approaches are apparent for characterizing and monitoring competing vegetation during the time between planting and crown closure. The first is to locate subplots randomly across the experimental unit, ensuring an unbiased estimate of total cover. This approach makes it difficult to distinguish between reductions in cover imposed by herbicide treatments and those imposed by increasing tree cover. Another approach is to first stratify the unit into those areas where vegetation is suppressed by tree crowns and those areas where it is not. This stratification is probably best achieved by estimating crown projection area from allometric relationships and establishing the proportion of this area where ground vegetation is eliminated.

The growth impact from a given level of competing vegetation probably differs by species contributing to total cover. The three CPT sites grew differing amounts of stem volume over the first 5 years. The effect of site on volume growth, however, may include many factors such as soil, climate, and treatment history, in addition to species of competing vegetation. At two other sites in western Oregon, 3 years of total vegetation control at one site resulted in 355% greater volume growth relative to the volume growth on the check plots over a 12 year period, but only 63% greater volume growth at a second site (Rose et al. 2006). This difference was attributable to overtopping hardwoods that severely suppressed the Douglas-fir trees at the first site. A similar growth impact occurred where juvenile height growth of naturally regenerating red alder (*Alnus rubra*) exceeded that of Douglas-fir (Harrington 1990). Control of only herbaceous plants in young loblolly pine stands has been shown to exacerbate the effects of competing vegetation by releasing fast-growing hardwoods (South et al. 2005; Miller et al. 2003). On corporate lands in the Pacific Northwest, 40% of the total area receiving post–site preparation control of competing vegetation was treated to deal specifically with hardwood competition (Briggs 2007).

Reduced herbicide efficacy in 2002 complicated the interpretation of volume growth response to delays in competing vegetation control. The goal of 25% maximum cover was attained at Seaside in 2002 for all regimes except OTTTT, but no regimes calling for treatment in 2002 achieved this goal at the other two sites. The year 2002 was the third growing season at Summit but the second growing season at both Seaside and Sweet Home; therefore, the treatments that were impacted varied by site. If all treatments were assumed effective in the regimes receiving four releases, then growth responses to the treatment delay suggested that the first year after planting is at least part of the critical period for Douglas-fir. Conversely, growth responses in regimes receiving three releases suggested that the second year was not part of the critical period, but this result was not consistent across sites because the target level of vegetation control (<25% total cover) was not achieved in all three treatment years at each of the sites. The significantly negative effect of delaying treatment at Sweet Home was consistent with the more rapid growth of competing vegetation during the first 2 years at that site, despite the fact that the second release in TTTOO was only partially effective (Fig. 1).

Age shift or time gain (Mason and Milne 1999) provided an estimate of the reduction in time required to achieve the same stem volume as that in stands with no treatment at 5 years. Age shifts are sometimes referred to as a type I gain (Mason and Milne 1999), i.e., a temporary increase in growth that causes cumulative growth to diverge for a short period of time and then become "parallel" through the rest of the rotation. This behavior is equivalent to a short-term divergence in relative growth rate followed by convergence back to a similar relative growth rate. Under this pattern of response, age shifts achieved early in stand development are implied to remain constant

The long-term fate of age shifts achieved early in the rotation are still uncertain in Douglas-fir; however, final yield gains can be large in other species that have been grown to full or near-full rotation age after early vegetation control (Wagner et al. 2005), suggesting that significant age shifts can be realized. Early-rotation age shifts have also been documented to diminish or disappear with increasing stand age. Among loblolly pine stands receiving different types of competing vegetation control, treatment of herbaceous vegetation caused a positive age shift early in stand development, but as woody species began competing with the pine, cumulative volume growth of the treated stand fell below that of the check plots (South et al. 2005). Conversely, where initial hardwood density was low, the age shift from early herbaceous control was stable from year 8 to 20. Although age shifts were not calculated, a similar pattern has been reported in Douglas-fir stands in the Pacific Northwest (Stein 1995; Rose et al. 2006). Where competing hardwoods are not an issue, the age shift from treating herbaceous vegetation will likely persist for longer time periods. While the future age shifts resulting from the CPT study treatments are unknown, the pattern of increase in age shift following cessation of weed control on the TTOOO and TTTOO treatments suggested that they will exceed the current maximum of 1.1 years and persist for a period of time that could be significant under relatively short rotations for Douglas-fir.

The similar age shift and final volumes from the TTTTT and TTTTO treatments (Fig. 5) suggested that the fifth year of treatment would be difficult to justify from both a biological and economic perspective. For any of the regimes involving two or more release treatments, age shifts showed an increasing trend, although the increase from both TTOOO and TTTOO decelerated after their last release. Age shifts induced by weed control in loblolly pine continued to increase after year 8 in some cases, but the duration of weed control ranged from 3 to 5 years (South et al. 2005). Mason and Milne (1999) reported an age shift of 0.5 years in radiata pine (*Pinus radiata* D. Don) from a one-time spot spray around subject trees. Age shifts from vegetation management in radiata pine growing in New Zealand ranged from 1 to 6 years over periods up to 18 years of age.

Current operational practice in young Douglas-fir plantations commonly involves one or two release treatments, best represented by the TOOOO and TTOOO treatments. At year 5 in the CPT study, the age shifts from 1 or 2 years of release were 0.1 and 0.75 years, respectively. The relatively small age shift resulting from 1 year of treatment may have been the result of the long-term efficacy of the preemergent site preparation herbicide, although differences in growth between the TTTTT and OTTTT treatments (Fig. 5) suggested otherwise. The difference in age shift between 1 and 2 years of initial release were continuing to increase at year 5, suggesting that the second year after planting was also part of the critical period for Douglas-fir.

Height growth

Height growth responses to the range of CPT treatment regimes illustrated potential biases in site index estimates from intensively managed plantations (Hanson 1997). In the Pacific Northwest, where the growing season is dominated by a pronounced summer drought, competing vegetation induces earlier onset of tree water stress (Newton and Preest 1988; Petersen et al. 1988; Dinger 2007), slowing photosynthesis and shortening the growing season. Douglas-fir height growth is determinant and generally finishes early in the growing season as available soil moisture diminishes; therefore, treatments that delay onset of water stress can increase height growth (Newton and Preest 1988; Petersen et al. 1988; Dinger 2007). Variation in height growth due to early-rotation treatments can frustrate efforts to estimate site index, particularly when equations constructed in natural stands are applied in intensively managed young plantations (Hanson 1997; Flewelling et al. 2001). In a quantitative comparison between plantation-estimated site indices and those based on previously measured natural stands, Flewelling et al. (2001) found that improvements in management between 1970 and 1990 increased 30 year Douglas-fir site index estimates by 60 cm every 5 years (Flewelling et al. 2001). However, in one Douglas-fir plantation, previously measured gains in height growth following herbicidal treatment were only temporary (Rose et al. 2006). Effects of competing vegetation treatments on height growth probably differ by site, with greater and longer lasting responses expected on xeric sites. Under these conditions, overstory dominance of the understory takes longer, and water is more limiting to tree growth (Monleon et al. 1999). Conversely, height growth effects are likely smaller where water stress is less pronounced, such as at the coastal Seaside site.

Conclusions

The development of competing vegetation cover under complex treatment regimes can be accurately quantified as a function of years since last release and number of prior releases. Annual tree growth likewise was accurately predicted from initial tree size and current vegetation cover. No cumulative effects of prior competition could be identified beyond those reflected in initial tree size at the start of each growing season. Direct effects of treatments were therefore inferred to be relatively short lived, but indirect effects continued to compound through the greater growth potential of larger trees. The evidence from this experiment suggests some gain by avoiding delays in release from competing vegetation.

Based on responses to the eight CPT study regimes, the critical weed-free period for maximizing yield in Douglas-fir was estimated to be a minimum of 2 years and maximum of 4. The upper limit is similar to results for eastern white pine (Wagner et al. 1999). However, responses that differed among sites for the delayed treatments suggested that the critical period also depends on factors such as the species of competing vegetation, as has been found for many agricultural crops (Zimdahl 1988). Critical period in this study of Douglas-fir plantations was defined by growth response to treatments implemented in the first 4 or 5 years after planting. Adaptation of the CP concept to forest crops requires recognition that early growth responses are relevant only to the extent that they indicate differences in final yield at a given age, or in age to reach a given yield. Ultimately, economic criteria must be superimposed on long-term biological responses to arrive at sound financial decisions about the intensity of competing vegetation control (Cousens 1987).

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