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Response of ponderosa pine plantations to competing vegetation control in Northern California, USA: a meta-analysis

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A meta-analysis was performed to determine response of stand basal area growth to competing vegetation control (CVC) in ponderosa pine (*Pinus ponderosa*) plantations grown at 29 sites across northern California. These studies were installed during the last 50 years on site indices from 11 to 35 m at 50 years and often included other treatments besides CVC. Our analyses showed, with considerable certainty, that the magnitude of the CVC effect on overall basal area increase was 80% (40%–105%). The 40% increase occurred 5 years and the 105% increase occurred 10 years after the treatment was applied. A 67% to 91% increase was found 15 to 30 years after CVC. Additional treatments such as fertilization and high stand density accelerated the CVC effect. The trends of the CVC effect not only varied with stand developmental stages but also differed where CVC treatments were applied to seedlings or to older plantations. Results suggest that productivity response to vegetation control increases during the stand initiation stage and peaks when stands are in the stem exclusion stage. Thus, the magnitude of CVC effect depends on when it is applied relative to the stage of stand development. Any factors that increase stand development will accelerate this process. Therefore, to capture early growth gains, stands must be thinned soon after the onset of inter-tree competition. Timing depends on site productivity and previous silvicultural treatments.

Introduction

Competing vegetation control (CVC) is a common forestry practice to speed stand development and to ensure adequate seedling survival and sufficient growth for certain plantations across the world.[1,2] Many studies demonstrate that CVC enhances stand productivity, with percentage volume gains ranging more than four orders of magnitude.[3] These results, especially those with very high enhancement, usually reflect a combination of growth reduction and lower survival in the control plots compared with plots with competing vegetation removal.[4] Furthermore, gains often vary by tree species,[5,6] treatment duration,[7,8] vegetation composition,[9–12] site quality,[8,10,13] silvicultural treatments[14,15] and other environmental factors.[3,8] For example, by summarizing numerous studies of radiata pine (*Pinus radiata*) in Australia and New Zealand, Richardson[7] found that volume gains following vegetation control decreased with the treatment duration, ranging from 1000% one year after planting to 80% after 10 years. From two experiments established at different sites in New Zealand, he found that stem volume was 54% higher in CVC plots than that in non-CVC plots at the site with annual rainfall of 1500 mm (but see Wagner *et al*.,[3]). However, volume gains were 400% at the site with lower annual rainfall (800 mm). The treatment effect lasted approximately 3 years at the former site, compared with 5 years at the latter site before the treated and untreated trends became parallel. The CVC effect was also associated with stand density of crop trees. Studying the relationship between stand density and shrub competition on stand dynamics of ponderosa pine (*Pinus ponderosa*) at three contrasting sites, Zhang *et al*.[8] found that not only did the CVC effect change the response magnitude over 35 years but also the timing of convergence of treated and untreated plots depended on stand density and site quality. Such inconsistent results and their associated factors made it difficult to describe a universal magnitude of the CVC effect and a comprehensive study is warranted.[16]

Since the concepts of two types of growth responses to silvicultural treatments were introduced,[17] they have been used to describe the CVC effect.[3,18] Type I response describes the parallel growth trends between treated and untreated stands after the duration of treatment effect. Type II response characterizes a long-term change in site properties so that a divergence of growth curves occurs between treated and untreated stands. Hence, different growth response types also affect our ability to estimate the CVC effect.

Experimental design could affect the estimate of CVC effect as well. For example, relatively small plot size causes significant

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Table 1 Site location and characteristics, additional treatments and associated information for the studies used in the meta-analysis of CVC effect

Site	Latitude (°N)	Longitude (°W)	Elevation (m)	Original study	Additional treatments	Age when CVC was first applied	Treatment years*	SI at 50 years	Soil series†	Reference
Aspen	40.72	121.09	1768	LTSP	Comp, OM	1	10	14.6	Inville	Powers[20]
Balderston 1	38.93	120.75	991	VMS	F	10	24	23.2	Cohasset	Powers *et al.*[21]
Balderston 2	38.93	120.75	991	VMS	F	10	24	10.7	Mariposa	"
Big Tunnel	39.31	120.77	1499	VMS	None	11	10	12.2	Crozier	Fiddler and McDonald[22]
Black Mountain	41.55	121.45	1646	WRS	None	28	20	22.0	Tionesta	Unpublished
Blodgett	38.89	120.64	1311	LTSP	Comp, OM	1	15	30.0	Cohasset	Powers[20]
Brandy	39.54	121.04	1128	LTSP	Comp, OM	1	10	29.0	Aiken	"
Bunchgrass	40.61	121.43	1570	LTSP	Comp, OM	1	10	14.9	Yallani	"
Central Camp	37.33	119.48	1646	LTSP	Comp, OM	1	10	24.0	Dome	"
Challenge 1	39.50	121.22	838	LTSP	Comp, OM	1	15	28.0	Aiken	"
Challenge 2	39.48	121.22	810	DS	Density	1	42	34.0	Sites	Oliver[15]
Chester	40.31	121.10	1533	GOE	F	1	24	20.0	Redriver	Powers and Ferrell[23]
Cone	40.73	121.12	1859	LTSP	Comp, OM	1	10	14.3	Inville	Powers[20]
Elk Springs	41.40	122.32	1259	VMS	None	1	31	12.2	Deetz	McDonald and Abbott[11]
Elkhorn	40.08	121.74	1539	GOE	F	1	20	17.0	Sheetiron	Powers and Ferrell[21]
Feather Falls	39.62	121.20	1250	GOE	F	1	20	35.0	Toadtown	"
Foresthill	39.17	120.68	1536	SPS	None	1	20	20.0	Crozier	Lanini and Radosevich[5]
Heliport	39.28	122.67	1294	DS	Density	11	35	17.0	Neuns	Oliver[24]
Jaws	41.89	123.06	1018	GOE	F	1	23	23.0	Holland	Powers and Ferrell[23]
Lowell Hill	39.26	120.78	1250	LTSP	Comp, OM	1	10	25.0	Cohasset	Powers[20]
Owl	37.24	119.41	1829	LTSP	Comp, OM	1	10	23.0	Chaix	"
Pondosa	41.21	121.63	1181	GOE	F	1	23	20.0	Jimmerson	Unpublished
Rogers	39.77	121.32	1250	LTSP	Comp, OM	1	10	27.0	Shaver	Powers[20]
Shasta	41.37	122.32	1356	FRS	None	35	5	18.0	Washougal	Unpublished
Third Water	39.83	121.04	1284	VMS	None	16	10	20.0	Kistirn	Fiddler *et al.*[25]
Vista	37.38	119.56	1585	LTSP	Comp, OM	1	10	18.0	Dome	Powers[20]
Wallace	38.97	120.52	1570	LTSP	Comp, OM	1	15	21.0	McCarthy	"
Whitmore 1	40.63	121.90	747	GOE	F	1	21	23.0	Aiken	Powers and Ferrell[23]
Whitmore 2	40.61	121.91	762	FRS	None	21	5	23.0	Aiken	Unpublished

LTSP, Long-term Soil Productivity Study; VMS, Vegetation Management Study; WRS, Black Mountain Windrow Soil Respreading Study; SPS, Site Preparation Study; DS, Density Study; GOE, Garden of Eden Study; FRS, Fuel Reduction Study; Comp, compaction; OM, organic matter removal; F, fertilization.
* Number of years for which CVC was applied.
† Soil series is based on United States Department of Agriculture–Natural Resources Conservation Service classification.

variation in volume estimation. In addition, the dynamics of both overstory trees and understory vegetation over time further complicates the magnitude of the treatment effect.[2] Successful plantation establishment depends on how fast trees can develop a continuous canopy.[19] The impact of CVC on stand development may impose negative or positive feedbacks to the CVC effect.[8] Therefore, a quantitative measure of the effect of vegetation management on forest productivity can only be developed over a long period, at multiple sites, with reasonable plot size, and at an acceptable stocking to draw a meaningful conclusion for forest land managers.

Over the past 50 years, scientists of the United States Department of Agriculture Forest Service and the University of California have established many long-term experiments to examine the effect of CVC on plantation establishment and stand development under a Mediterranean climate throughout northern California. Here, we reanalyze data collected from these research projects where CVC was at least one of the treatments. We focus only on ponderosa pine (*P. ponderosa* Lawson & C. Lawson var. *ponderosa*), one of the most important timber species in California. Not only does it dominate in the yellow pine zone of the Sierra Nevada, Klamath and the Southern Cascades, but it is also a keystone species in mixed-conifer forests throughout the region.

In this review, we used meta-analysis to summarize the long-term treatment effects of CVC on growth of ponderosa pine plantations. Two specific objectives were (1) to determine the magnitude and significance of the effect of controlling competing vegetation on basal area (BA) growth and (2) to examine how site index (SI; a species-specific measure of forest productivity, expressed as the average height of trees in a stand at specific age), duration of vegetation control, stand developmental stage, and such additional treatments as density manipulation, fertilization, and so on, affect the magnitude of vegetation control responses.

Methods

The database

Studies that were established during the latter half of the last century were included.[5,8,11,13,15,20,22,24–26] Some results from these studies were published in refereed journals or station research reports. Some have not been published but were included to avoid biasing towards studies with positive results. Because both nonpublished latest data and original data are available for the current report, we do not face the inconsistency of reporting variables in the original papers. As long as we were aware, no other published studies met our standards (see next paragraph) for ponderosa pine in California.

The criteria for the studies to be included in this review were as follows: (1) CVC must be one of the treatments in the study; (2) both vegetation treatment and control must be replicated at least twice, regardless of whether additional treatments were included; (3) number of trees in the experimental unit, usually plot or subplot, must be more than 15 or plot size being at least 0.01 ha; (4) survival rate was at least 75%; (5) plot or subplot size must be the same between treatment and control; (6) a difference in the number of living trees between treated and control plots should be less than 15% when measurements were conducted; (7) at least 85% of trees are ponderosa pine; (8) for studies where treatment was applied to seedlings, study duration must be at least 5 years; and (9) for those studies established in older plantations, trees must have been measured at least twice, immediately after the treatment and again at 5 or more years later.

These criteria generated 29 study sites for analysis (Table 1), ranging from an SI of 11 to 35 m at 50 years. Because most studies also included additional treatments combined with vegetation control, 221 comparisons between full and no removal of competing vegetation were generated. The other treatments included stand ŋdensity manipulations,[26,27] with and without fertilization applied exponentially for the first 6 years[13,23] or applied once,[21] soil compaction and organic matter removal before planting[20] and other practical management regimes. It is worth noting there were always a CVC and non-CVC regardless of additional treatments. For example, a combination of five stand densities with and without vegetation control yielded five comparisons. Techniques used to control competing vegetation were mainly manual or mechanical removal for study plots established in older plantations and herŋbicide applications during early plantation establishment (<10 years) for study plots established from seedlings. The rates and brands of herbicides were contemporary chemicals in forest practice (e.g. 2,4-dichlorophenoxyacetic acid, 2,4,5-trichlorophenoxy, glyphosate or hexazinone). Although the frequency of the CVC application varied across studies, understory vegetation seemed to be effectively controlled. This is particular true for the dominant shrubs, mainly *Arctostaphylos* spp. and *Ceanothus* spp. at all these study sites. Therefore, we assumed the CVC occurred during the entire treatment years. We focus on BA because it can easily be measured directly and with minimal error. Response was measured as BA increment between the time when CVC was applied and the subsequent measurement year.

We analyzed data based on treatment durations of 5, 10, 15, 20, 25 and 30 years because most meta-analysis methods require observations to be independent from one another. Because there were a few studies that were not measured at exactly every 5 years, we assigned them to the closest age classes. For example, if inventory was performed after 12 and 24 years of CVC, we treated 12 to be 10 and 24 to be 25. The multiple measurements across years on individual plots or subplots on our study sites were analyzed separately. Although we could have combined time points as recommended by Borenstein *et al.*,[27] we would lose the opportunity to examine the relationship between overstory and understory vegetation across the stand developmental stages, which is one of the objectives of this study.

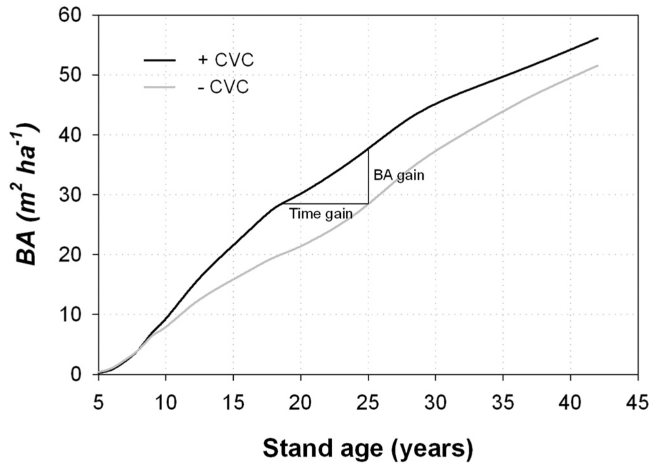

Figure 1 Example of obtaining time gain and BA gain between vegetation absent (+CVC) and vegetation presence (−CVC) at 25 years in the treatment of 480 trees per hectare at the Challenge Density Study.

Meta-analysis procedure

Meta-analysis requires estimates of treatment effect size (E); the magnitude of the CVC treatment mean relative to the control mean E_i ($i = 1, 2, \ldots, 221$) for each of the 221 pairs was estimated with the natural logarithm of the response ratio: $E_i = \ln(R_i) = \ln(X_{ie}) - \ln(X_{ic})$, where R_i is the response ratio and X_{ie} and X_{ic} are the treatment mean and the control mean, respectively.[27,28] By using $\ln(R_i)$, we not only linearized the metric but also normalized the sampling distribution of R_i.[28] The variance and 95% confidence interval (CI) for individual log response ratios was computed with MetaWin 2.0[29] following the formula of Hedges *et al.*[28]

Two approaches were used to analyze these data. First, we used the weighted maximum likelihood estimation of parameters for testing H_0: $\text{Ln}(R) = 0$ using SAS 9.3 PROC MIXED (SAS Institute, Cary, NC). Second, a test of the hypothesis that the between-experiment variance component is zero H_0 $\sigma^2 = 0$ at significance level $\alpha = 0.05$ based on the Q statistic computed from MetaWin 2.0.[29] If a significant heterogeneity was found, we further explored how additional treatments, stand initial age, Stand Density Index (SDI) of CVC plots and SI influenced the controlling vegetation effect. The former two variables were treated as categories in subgroup meta-analysis, and the latter two were treated as continuous variables with meta-regression. The effects of each individual independent variable were characterized using a one-way mixed model with MetaWin 2.0. The model sum of squares for each factor was used to quantify the heterogeneity in effect size explained by categorical factors (Q_B) or continuous factors (Q_M). The ratio of Q_B or Q_M and the total heterogeneity in effect size (Q_T) is analogous to the coefficient of determination (R^2). For category treatments, we calculated effect size and 95% CI for each variable. For continuous variables, we obtained estimates and standard errors around the regression slope and intercept.[29]

Time-gain analysis

Time gain and BA gain of CVC stands were estimated for the Challenge Density Study because trees on this study were measured multiple times for at least 40 years. We adopted the method of Mason[18] by plotting BA against stand age for both CVC treatment (+CVC) and non-CVC treatment (−CVC) (Figure 1) to graphically measure the time gain or BA gain at particular years. For the sake of simplicity, we only included the highest, the lowest and the intermediate densities with a 5-year interval from 10 to 40 years.

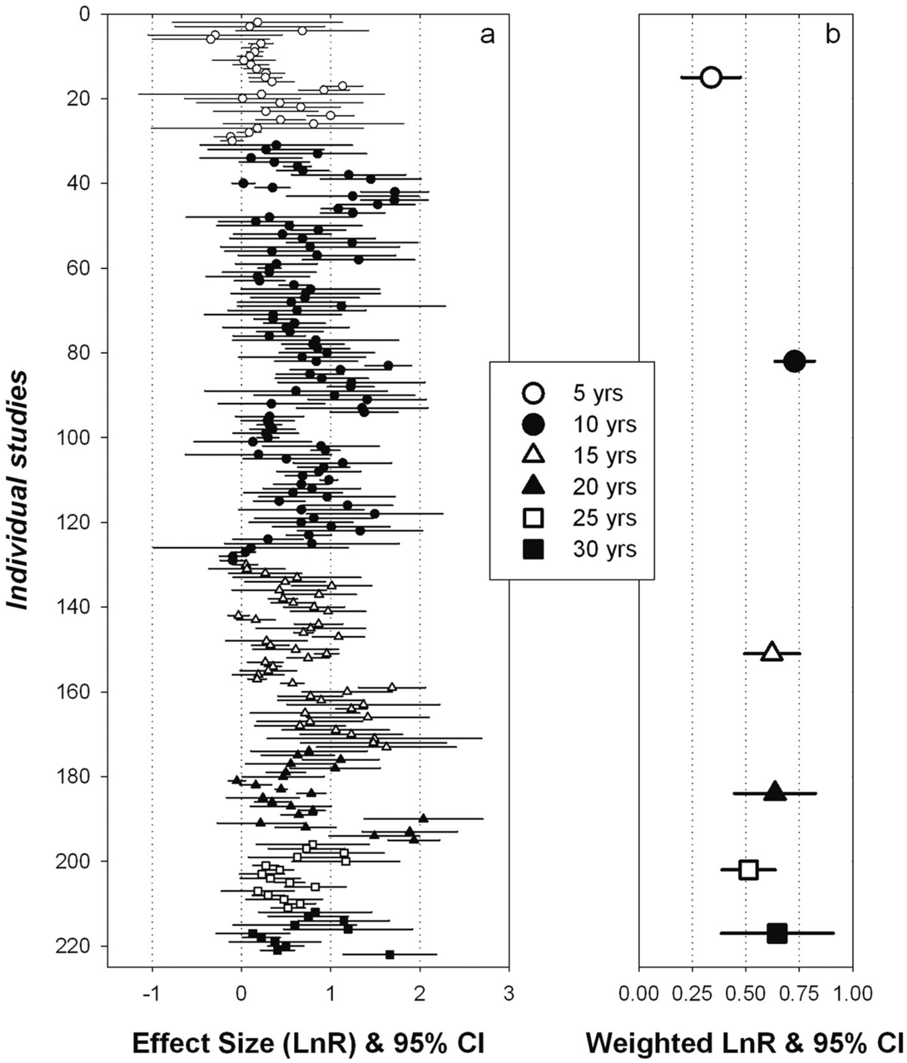

Figure 2 (a) Log ratios and 95% CI for individual studies and (b) weighted effect size (LnR) and 95% CI for different number of treatment years of CVC effect on BA growth as reported in 221 different comparisons within 29 study sites for ponderosa pine plantations grown in northern California across 30 years.

Results

Of the 221 ratios of CVC treatment mean to control mean at 29 study sites, 26 were at 5 years after CVC treatment, 96 at 10 years, 47 at 15 years, 25 at 20 years, 16 at 25 years and 11 at 30 years (Figure 2a). The fewer pairs at 5 years compared with those at 10 years were because trees did not reach breast height (1.37 m) at many sites. Although some study sites were measured after more than 30 years (Table 1), the numbers of pairs were too small to do a meaningful meta-analysis.

Weighted effect sizes (LnR) were all significantly greater than zero, with LnR being 0.34 (95% CI, 0.18–0.49; $t_{25} = 4.52$; $P < 0.001$) after 5 years of treatment, 0.72 (95% CI, 0.64–0.82; $t_{95} = 16.37$; $P < 0.001$) after 10 years of treatment, 0.63 (95% CI, 0.49–0.76; $t_{45} = 9.40$; $P < 0.001$) after 15 years of treatment, 0.66 (95% CI, 0.41–0.89; $t_{24} = 5.63$; $P < 0.001$) after 20 years of treatment, 0.51 (95% CI, 0.39–0.64; $t_{15} = 8.72$; $P < 0.001$) after 25 years of treatment and 0.66 (95% CI, 0.37–0.95; $t_{10} = 8.72$; $P < 0.001$) after 30 years of treatment (Figure 2b). These numbers indicate that CVC increased BA by 40% to 105% (derived by $(e^{\text{LnR}} - 1) \times 100$ from Figure 2b), varying with number of treatment years. The overall trend showed positive but relatively low response ratios 5 years after CVC, rising by 10 years but declining slightly although not significantly thereafter (Figure 2).

Trends in positive BA responses to the CVC over time depended on plantation ages when treatments were applied (Figure 3). Five years after treatment, the CVC effect was significantly higher ($Q_B = 7.11, P = 0.008$) in study plots initiated from seedlings than that in plots from older plantations; the percentage increases were 76% in the former versus 26% in the latter. The trend was the same 10 years after the treatment, but only significant at $P = 0.075$ ($Q_B = 3.17$) with 113% increase when CVC was applied to seedlings and 58% when applied to older plantations, respectively. The difference was significant after 15 years (99% *vs* 53%, $Q_B = 3.91$, $P = 0.048$) but nonsignificant after 20 years (106%

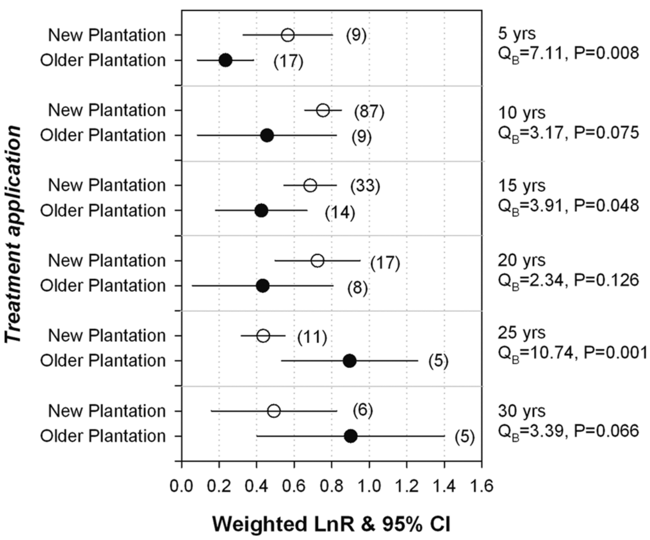

Figure 3 Weighted effect size (LnR) and 95% CI of the CVC effect on BA between studies where treatment was applied to new plantations (open symbols) and to older plantations (closed symbols) for different number of treatment years. Numbers in parentheses are the number of pairs included.

vs 54%, $Q_B = 2.34$, $P = 0.126$). After 25 years, the effect of CVC was not only significant but reversed ($Q_B \geq 10.74$, $P = 0.001$) with a much lesser CVC effect in study plots receiving treatment as seedlings (55%) than when older plantations were treated (145%). Although less significant, this trend held to 30 years ($Q_B = 3.39$, $P = 0.066$).

Similar results were found for additional treatments (Figure 4) across the treatment years, with significant differences among treatments after 5 years ($Q_B = 11.14$, $P = 0.025$). However, the difference was not significant among treatments from 10 to 25 years ($Q_B \leq 14.53$, $P \geq 0.105$), although several treatments differed among individual studies and treatment years (Figure 4). Of additional treatments, fertilization and density were measured at least four times during the observation period. Analysis indicated that fertilization enhanced the vegetation control effect by 12% (87% for the nonfertilized treatment *vs* 99% for the fertilized treatment) after 5 years (Figure 5). However, at 10 years, the trend reversed and the response was greater for the nonfertilized treatment (180%) versus the fertilized treatment (174%) and remained that way in subsequent years (70% *vs* 106% at 15 years, 34% *vs* 60% at 20 years and 42% *vs* 66% at 25 years, respectively).

The impact of density on the CVC effect was further examined using the Challenge Density Study, which has been maintained for 42 years and measured more frequently than any other study in our database. Not only was the CVC effect positive when treatment duration was less than 30 years (Figure 6), but the maximum increases peaked at different years between age 10 and 20 years depending on the density treatment. After 20 years of treatment, the magnitude of the CVC effect gradually decreased for all densities. After 42 years of treatment, the CVC effect disappeared (−2%) in the highest density treatment (2990 trees per hectare), whereas percentage increase was 9% in the 1330 trees per hectare and approximately 19% in the other density treatments.

Meta-regression showed that regression models were significant with effect size as the dependent variable and SI as the independent variable at treatment years 15, 20 and 30, or SDI as the independent variable (calculated from CVC plots only) in treatment years 5, 10, 15, 20 and 25 (Table 2). The ratio between Q_M and Q_T was generally low, ranging from 0.00 to 0.74 for SI and from 0.04 to 0.40 for the SDI across different treatment years. The highest ratio (0.74) for SI at 30 years included only 11 pairs at three sites.

Our time-gain analysis for the Challenge Density Study showed that time gain peaked at 25 years after the CVC treatment; the magnitude differed approximately 5 years in the highest density plots and approximately 8 years in lower density plots (Figure 7). However, the highest BA gain occurred at 15 years after the treatment for all densities although there was no difference in BA gain between 10 and 15 years in the highest density plots. After their peak gains, both time gain and BA gain decreased gradually to zero at 40 years after treatment was applied in the highest density plots. In lower density plots, time gain held constant, but BA gain fell from 60% to 20% during the last 15 years.

Discussion

Vegetation control significantly increased stand growth for at least 30 years, regardless of whether competing vegetation was removed at the seedling stage or from an older plantation. The positive effect of vegetation control on crop trees has been broadly reported. Several recently published reviews offer excellent summaries about the effects of vegetation management on growth.[3,9,26] Our meta-analysis provides a point estimate, with considerable certainty, of the magnitude of the CVC effect on stand BA growth of ponderosa pine plantations. Depending on the duration of treatment, BA increased by 40% to 105% (Figure 2b), showing much less variation than the 4% to 11800% summarized by Wagner *et al*.[3] for the volume gains across the Pacific Northwest forests.

Another factor influencing the CVC effect between treated and control stands can be differences in survival rate.[4] In this study, we focused only on the growth effect of vegetation control. Treatments that were applied to seedlings in this study were established after complete site preparation that removed all standing vegetation from the sites.[5,15,20,23,26] The seedlings were carefully raised in dependable nurseries and the survival of ponderosa pine seedlings was high. The studies where treatment was applied to older plantations were also planted on either site-prepared ground or after a stand-replacing wildfire.[21,22,24,25] Furthermore, the older plantations were selected based on their uniformity, and growth increment was used to calculate the CVC effect. All these selection criteria assured that we concentrated only on growth differences caused by the CVC effect. In addition, our analyses called for a reasonable plot size, which assures that results can be directly applied to a regeneration program. Therefore, the point estimates and their CIs (Figure 2) are less variable than previously reported and can be a valuable guidance to forest managers.

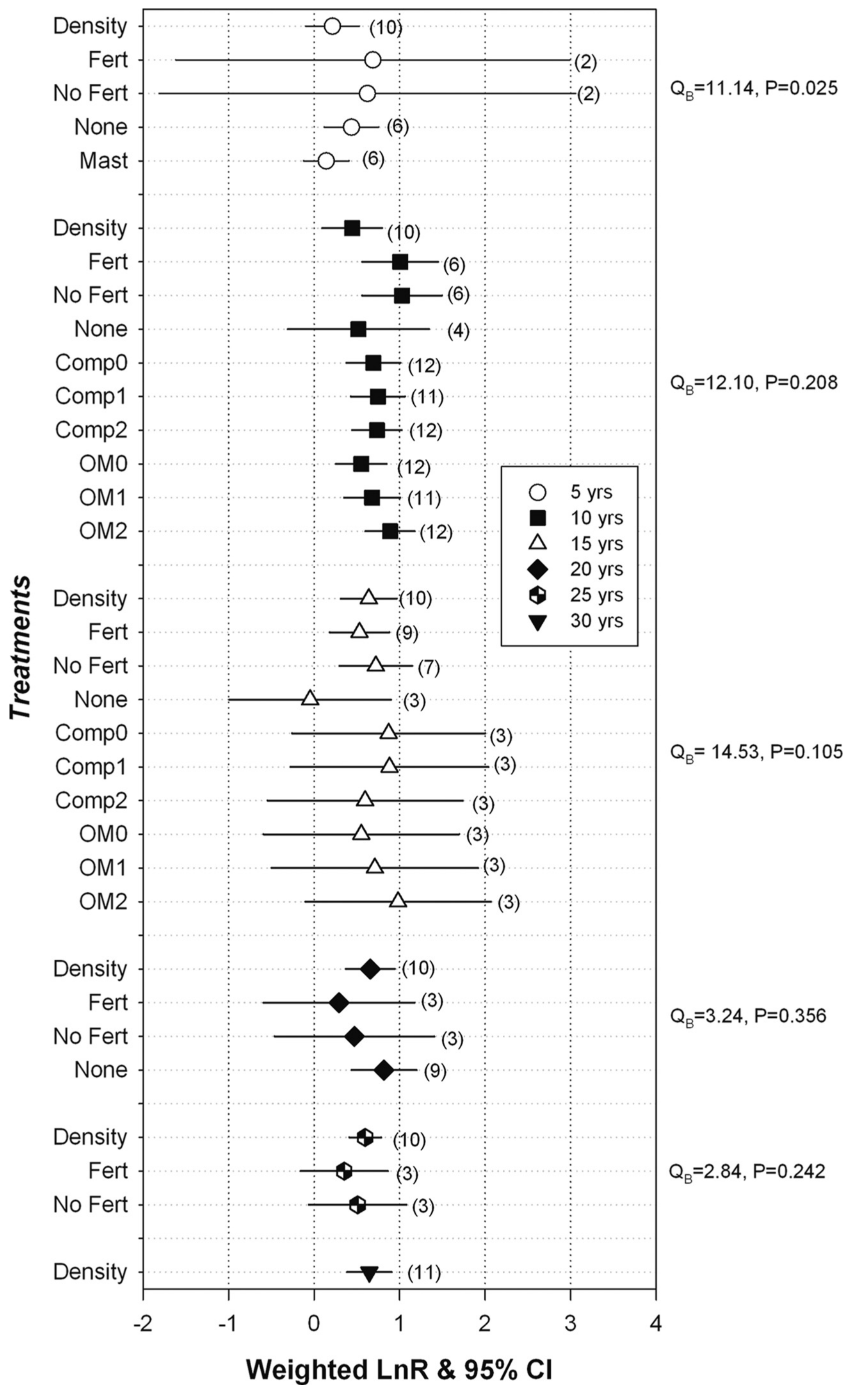

Figure 4 Weighted effect size (LnR) and 95% CI of the CVC effect on BA among additional treatments on each study site over differing treatment years. Numbers in the parentheses are the number of pairs included. Treatment abbreviations as described in Table 1.

Significant heterogeneity in the effect size can be explained by additional treatments in each of the original studies. Using fertilization as an example, we found that the CVC effect was higher in fertilized than that in nonfertilized treatments at shorter treatment duration (Figure 5). For treatment durations of 10 or more years, the effect was reversed. The phenomena apparently related to stand development stages.[19] When a plantation is in its stand initiation stage, any treatment such as fertilization that enhances tree or stand growth will increase the CVC effect (LnR = X_e/X_c). Because shrubs and other weeds are aggressive competitors for nutrients, stand growth would be proportionally higher in the absence of competing vegetation than that in the presence of vegetation in the fertilized treatment. For example, X_e and X_c of BA were 5.77 and 2.29 m^2 ha^{-1}, respectively (152%

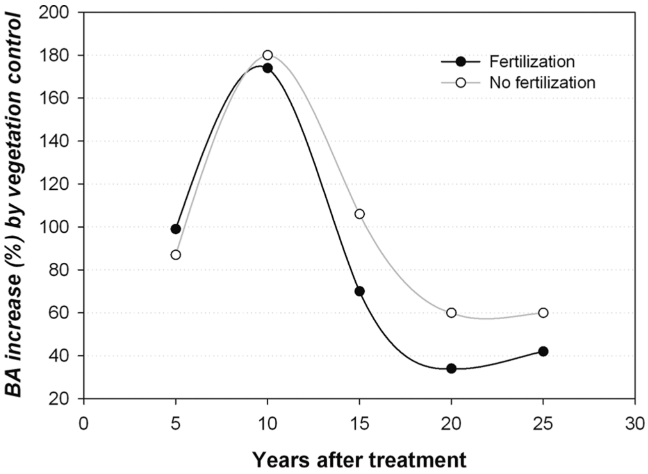

Figure 5 The effect of fertilization on percent increases in BA response to CVC on six study sites during the 25 treatment years. Some sites were not measured at each 5-year interval.

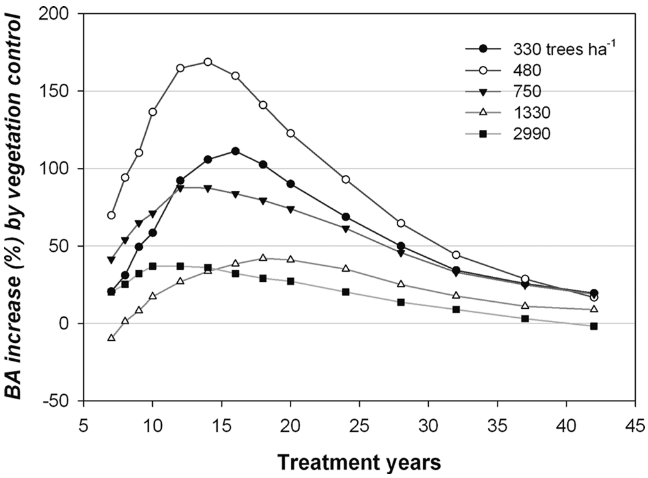

Figure 6 The effect of stand density on percentage in BA response to CVC in the Challenge Density Study from 7 to 42 years after treatment. Plantation was planted with density of 330, 480, 750, 1330 and 2990 trees per hectare.

increases by vegetation control), in the nonfertilized treatment at Whitmore Garden of Eden site at age 5 years, whereas the X_e and X_c were 7.21 and 2.32 $m^2\ ha^{-1}$ (211% increases) in the fertilized treatment.

Inter-tree competition will slow individual tree growth in the developing plantation. This begins sooner when vegetation is controlled because tree-shrub competition is absent. Hence, the CVC stands will reach the stem exclusion stage sooner.[19] In contrast, in the non-CVC stands, tree-shrub competition impedes stand development, delaying the onset of inter-tree competition. Consequently, the no-CVC treatment stays in the stand initiation stage. Therefore, the CVC effect (LnR) might reach maximum value at this period; the duration depends on how fast the no-CVC stands develop.

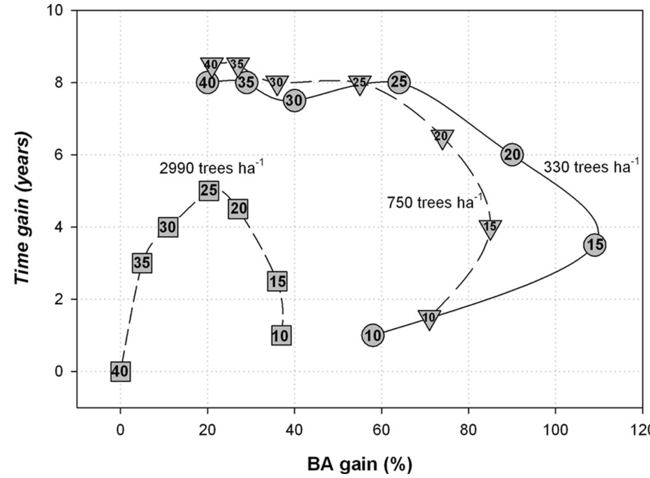

Figure 7 The effect of CVC on time gain and percentage of BA gain for ponderosa pine planted with density of 330, 750 and 2990 trees per hectare in the Challenge Density Study from 10 to 40 (number in symbols) years after the treatment.

As the stand further develops, the vigor of the understory vegetation will decline as the developing canopy reduces the light reaching the understory. Thus, tree growth rate will increase in the non-CVC treatment while tree-shrub competition decreases. Furthermore, diverse plant species in this treatment might improve soil quality and other resources (Busse *et al.*,[14] W.R. Horwath and R.F. Powers, personal observation), suggesting more resources for growth in the no-CVC treatment. Because inter-tree competition is much stronger in the vegetation controlled treatment than that in the nonvegetation controlled treatment,[8] the magnitude of the CVC effect would diminish and might only carry over the benefit from the previous years (i.e. lower density in Figures 6 and 7) or gave up gains from the previous years (i.e. 10 years after the treatment in Figure 5 and the highest density in Figures 6 and 7). Fertilization accelerated this process by shortening developmental years compared with trees in the nonfertilized treatment (Figure 5). The trend of the CVC effect on BA comes with a caveat: not only do vegetation control and fertilization accelerate stand development during 5 to 10 years, but they also enhance tree size and plantation uniformity for a long period.[32] Because plantations in this stage would be thinned in general forest practice, the positive CVC effect would be kept from both removed BA and future BA growth of remaining trees. Without artificial thinning, we expect that a self-thinning effect replaces the CVC effect, which can only be tested if these studies continue to be measured.

A larger effect of CVC was found when applied to seedlings than to the older plantations (Figure 3). Plantation age when the CVC treatment was applied varied during 35 years (Table 1), covering a range of developmental stages. Difference in LnR between the CVC applied to seedlings and to older plantations after five treatment years is almost certainly comparing two different developmental stages. Nonetheless, tree ages in the older plantation were the same in CVC plots and control plots before the treatments. After treatment commenced, trees in the treated plots apparently needed some years to build leaf

Table 2 Intercept, slope, Q_M and significance level from the meta-regression with the effect size as a dependent variable and either SI or SDI as a covariate for each of the treatment years

Treatment years	SI					SDI				
	Intercept (SE)	Slope (SE)	Q_M	P	Q_M/Q_T	Intercept (SE)	Slope (SE)	Q_M	P	Q_M/Q_T
5	0.358 (0.227)	−0.001	0.01	0.926	0.00	0.575 (0.118)	−0.002	5.25	0.022	0.14
10	1.011 (0.178)	−0.012	2.77	0.096	0.03	0.894 (0.104)	−0.002	3.14	0.077	0.04
15	1.181 (0.265)	−0.022	4.66	0.031	0.09	1.193 (0.194)	−0.003	10.07	0.001	0.17
20	1.423 (0.325)	−0.033	6.35	0.012	0.16	1.312 (0.238)	−0.003	9.44	0.002	0.22
25	0.840 (0.226)	−0.013	2.21	0.137	0.13	1.015 (0.168)	−0.002	10.31	0.001	0.40
30	1.716 (0.241)	−0.040	25.92	0.000	0.74	1.120 (0.563)	−0.002	0.71	0.398	0.06

The ratio (Q_M/Q_T) was calculated to be analogous to the coefficient of determination (R^2).

area before increasing diameter growth (Ritchie *et al.*, in review). Therefore, the CVC effect (LnR) was smaller in these older plantations than that in the seedling-initiated stands in the earlier years (Figure 3). Later, because the control plots were heavily occupied with shrubs for many years, trees in these plots grew very slowly,[8] which also increased the relative CVC effect (LnR).

Several questions remain. If our argument is right, a significant Q_M and a high coefficient of determination should be found in the meta-regression between the effect size and either SI or SDI. The Q_M was significant for SI in three of six treatment years and for SDI in four of six treatment years (Table 2), which seems to support our hypotheses that these stand variables affect the growth response magnitude to CVC. However, only a small amount of variation in the CVC effect can be explained by either variable (Table 2). Apparently, a more complex model is needed to characterize the CVC effect. Balandier *et al.*[28] provide a conceptual model by considering the dynamics of the entire plant community. Unfortunately, variables related to this model were not measured in these studies.

Second, stand density influences the CVC effect (Figure 6). We would expect that high-density stands accelerated crown closure faster and therefore the peak of the CVC effect would be earlier. This was true for the treatment with the highest density (2990 tree per hectare), but not with the 1330 tree per hectare. Without this density treatment, all others would support our hypothesis. Once again, the plant community could have differed significantly,[9,26] especially among different overstory densities. Future studies may need to pay more attention to the competing vegetation dynamics.

Finally, results from the time-gain analysis[18] revealed that both time gain and BA gain from CVC appeared to relate to stand development, with maximum BA gain occurring before the canopy closure and maximum time gain occurring before the self-thinning or intensive inter-tree competition (Figure 7). A decreasing BA growth and time gain on the highest density with 2990 trees per hectare at the Challenge Density Study suggests that the CVC effect followed a type 1 response[17] that “advances stand development through a phase of rapid early growth, but does not affect peak productivity”.[30] However, a constant time gain relative to the BA gain on other densities (i.e. 330 and 750 trees per hectare) indicated that trees in these plots had not reached the self-thinning stage (Figure 7). It appears that any silvicultural treatments that speed stand development will reduce time gains by accelerating a plantation to reach target BA.[8] Once again, the magnitude of CVC effect was related to stand development on both stand growth and time gain. Because plantations were usually managed for wood or biomass production, disturbance resilience and other ecosystem services in the region,[31,32] maximum BA gain and time gain can be only kept if a silvicultural thinning is conducted before or in the early stage of stem exclusion.

Conclusions

Our analyses showed, with considerable certainty, that the magnitude of the CVC effect on stand BA increases by 40% to 105%, depending on duration of treatment. The additional treatments in the original studies influenced the CVC effect. Fertilization and high-density accelerated the CVC effect. The trends of the CVC effect varied with stand developmental stages. In addition, the effect varied with stands depending on whether CVC was applied to seedlings or to older plantations. Results suggest that the response of productivity to vegetation control increases during the stand initiation stage and peaks when the CVC stands are in their stem exclusion stage. Then, the magnitude of CVC effect depends on developmental rate of both CVC and no-CVC stands. Any factors that increase stand development will accelerate this process. Therefore, to capture early growth gains, stands must be thinned soon after onset of inter-tree competition. Timing depends on site productivity and previous silvicultural treatments.

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References

1 Newton, M. 2006 Taking charge in forest vegetation management. *Can. J. For. Res.* **36**, 2357–2363.

2 Tappeiner, J. C. II, Maguire, D.A. and Harrington, T.B. 2007 *Silviculture and Ecology of Western U.S. Forests*. Oregon State University Press, Corvallis, OR, USA. pp. 332–356.

3 Wagner, R.G., Little, K.M., Richardson, B. and McNabb, K. 2006 The role of vegetation management for enhancing productivity of the world's forests. *Forestry* **79**, 57–79.

4 Hytönen, J. and Jylhä, P. 2011 Long-term response of weed control intensity on Scots pine survival, growth and nutrition on former arable land. *Eur. J. For. Res.* **130**, 91–98.

5 Lanini, W.T. and Radosevich, S.R. 1986 Response of three conifers to site preparation and shrub control. *For. Sci.* **32**(1), 61–77.

6 Zutter, B.R., Glover, G.R., Mitchell, R.J. and Gjerstad, D.H. 1997 Response of loblolly pine and sweetgum to intra- and inter-specific competition and influence of soil organic matter. *Can. J. For. Res.* **27**, 882–899.

7 Richardson, B. 1991 The effects of weeds on tree growth. In *Efficiency of Stand Establishment Operations*. M. Menzies, J. Parrott and L. Whitehouse (eds). Proceedings of an IUFRO Conference Rotorua, 1989. *Forest Research Institute Bulletin* No. **156**, pp. 242–249.

8 Zhang, J.W., Oliver, W.W. and Busse, M.D. 2006 Growth and development of ponderosa pine on sites of contrasting productivities: relative importance of stand density and shrub competition effects. *Can. J. For. Res.* **36**, 2426–2438.

9 Balandier, P., Collet, C., Miller, J.H., Reynolds, P.E. and Zedaker, S.M. 2006 Designing forest vegetation management strategies based on the mechanisms and dynamics of crop tree competition by neighboring vegetation. *Forestry* **79**, 3–27.

10 Devine, W.D., Harrington, T.B., Terry, T.A., Harrison, R.B., Slesak, R.A., Peter, D.H. *et al.* 2011 Five-year vegetation control effects on aboveground biomass and nitrogen content and allocation in Douglas-fir plantations on three contrasting sites. *For. Ecol. Manage.* **262**, 2187–2198.

11 McDonald, P. M. and Abbott, C.S. 1997 *Vegetation trends in a 31-year-old ponderosa pine plantation: effect of different shrub densities*. US Department of Agriculture, Forest Service, Research Paper PSW-RP-231, Pacific Southwest Research Station, Albany, California, USA. 35p.

12 Miller, J.H., Zutter, B.R., Newbold, R.A., Edwards, M.B. and Zedaker, S.M. 2003 Stand dynamics and plant associates of loblolly pine plantations to midrotation after early intensive vegetation management—a southeastern United States regional study. *South. J. Appl. For.* **27**, 2221–236.

13 Powers, R. F. and Reynolds, P.E. 1999 Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient. *Can. J. For. Res.* **29**, 1027–1038.

14 Busse, M.D., Cochran, P.H. and Barrett, J.W. 1996 Changes in ponderosa pine site productivity following removal of understory vegetation. *Soil Sci. Soc. Am. J.* **60**, 1614–1621.

15 Oliver, W.W. 1990 Spacing and shrub competition influence 20-year development of planted ponderosa pine. *West. J. Appl. For.* **5**(3), 79–82.

16 Ammer, C., Balandier, P., Bentsen, N.S., Coll, L. and Lof, M. 2011 Forest vegetation management under debate: an introduction. *Eur. J. Forest Res.* **130**, 1–5.

17 Snowdon, D. and Waring, H.D. 1984 Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. In *Proceedings, IUFRO Seminar on Site and Productivity of Fast Growing Plantations.* Pretoria/Pietermaritzburg, South Africa, pp. 701–710.

18 Mason, E.G. 1992 *Decision support systems for establishing radiate pine plantations in the Central North Island of New Zealand*. Ph. D. thesis, University of Canterbury, New Zealand.

19 Oliver, C.D. and Larson, B.C. 1996 *Forest stand dynamics*. McGraw-Hill Inc., New York.

20 Powers, R. F. 2006 Long-term soil productivity: genesis of the concept and principles behind the program. *Can. J. For. Res.* **36**(3), 516–528.

21 Powers, R.F., Young, D.H., Fiddler, G.O. and Spear, T.H. 2004 Balderston plantation revisited: a tale of two sites 25 years after treatments. In *Where We've Been, Where We Are, and Where We're Going*. Cooper, S.L. (comp.). Proceedings of the 25th Forest Vegetation Management Conference; January 20–22; Redding, CA. University of California, Shasta County Cooperative Extension, Redding, CA. pp. 61–72.

22 Fiddler, G.O. and McDonald, P.M. 1997 Mechanical and chemical release in a 12-year-old ponderosa pine plantation. US Department of Agriculture, Forest Service, Research Paper PSW-RP-232, Pacific Southwest Research Station, Albany, California, USA. 12p.

23 Powers, R.F. and Ferrell, G.F. 1996 Moisture, nutrient, and insect constraints plantation growth: the "Garden of Eden" study. *New Zealand J. For. Sci.* **26**(1/2), 126–144.

24 Oliver, W.W. 1984 Brush reduces growth of thinned ponderosa pine in Northern California. US Department of Agriculture, Forest Service, Research Paper PSW-RP-172, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA. 7p.

25 Fiddler, G.O., McDonald, P.M. and Mori, S.R. 2000 Mechanical and chemical release treatments applied to a 16-year-old pine plantation. US Department of Agriculture, Forest Service, Research Note PSW-RN-425, Pacific Southwest Research Station, Albany, California, USA. 11p.

26 McDonald, P. M. and Fiddler, G.O. 2011 Twenty-five years of managing vegetation in conifer plantations in northern and central California: results, application, principles, and challenges. US Department of Agriculture, Forest Service, General Technical Report PSW-GTR-231, Pacific Southwest Research Station, Albany, California, USA. 87p.

27 Borenstein, M., Hedges, L.V., Higgins, J.P.T. and Rothstein, H.R. 2009 *Introduction to Meta-Analysis*. Wiley, West Sussex, UK.

28 Hedges, L.V., Gurevitch, J. and Curtis, P.S. 1999 The meta-analysis of response ratios in experimental ecology. *Ecology* **80**(4), 1150–1156.

29 Rosenberg, M.S., Adams, D.C. and Gurevitch, J. 2000 *MetaWin, Version 2.0: Statistical Software for Meta-analysis*. Sinauer, Sunderland, MA, USA.

30 Snowdon, P. 2003 Growth of *Pinus elliottii*, *P. pinaster* and *P.* radiata on coastal dune soils near Jervis Bay, Australian Capital Territory. *Aust For* **66**(3), 161–169.

31 Oliver, W.W. 1997 Twenty-five-year growth and mortality of planted ponderosa pine repeatedly thinned to different stand densities in northern California. *West. J. Appl. For.* **12**(4), 122–130.

32 Zhang, J.W., Powers, R.F. and Skinner, C.N. 2010 To manage or not to manage: the role of silviculture in sequestering carbon in the specter of climate change. In *Integrated Management of Carbon Sequestration and Biomass Utilization Opportunities in a Changing Climate*. T.B. Jain, R.T. Graham and J. Sandquist (tech. eds.), pp. 95–110. Proceedings of the 2009 National Silviculture Workshop, June 15–18, 2009; Boise, Idaho. RMRS-P-61.