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ScienceDirect

Forest Ecology and Management 255 (2008) 2771–2781

Forest Ecology and Management

www.elsevier.com/locate/foreco

Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests

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Received 18 September 2007; received in revised form 16 January 2008; accepted 17 January 2008

Abstract

We examined 5-year basal area growth of nearly 2600 trees in stem-mapped plots at five locations differing in site characteristics, species composition, and management history on the Olympic Peninsula in Western Washington, USA. Our objectives were to determine if internal edges, the boundaries within the stand between components of the variable-density thinning, influenced individual tree growth, and whether incorporation of individual tree local competition indices in growth prediction models could account for treatment and edge effects. Treatment significantly affected tree growth at all sites, with trees in the thinned matrix displaying on average over 25% greater basal area growth than trees in unthinned patches. Proximity to canopy gaps created as part of the variable-density thinning increased basal area growth of trees in the thinned matrix by nearly 11%. In addition, growth of trees close to skid trails was 11% greater than trees located away from the trails. Past thinning history, and its effect on initial stocking rate, appeared to affect the magnitude of the edge effects. Blocks that had received earlier commercial thinnings, and thus had lower stocking at the onset of the study, displayed lower growth responses than previously unthinned blocks. Including local competition indices in the models generally reduced growth prediction error; however, the indices examined did not fully account for treatment or edge effects. Our results suggest that not accounting for internal edges in spatially complex stands could result in errors in projected growth of trees, although these edge effects are highly variable. Failure to account for the effects of internal edges could affect not just estimates of future stand yield, but also projections of future stand structure.

Published by Elsevier B.V.

Keywords: Variable-density thinning; Basal area growth; Competition indices; Canopy gaps; Skid trails; Edge effects

1. Introduction

Greater recognition of the ecological importance of forest structural and compositional complexity has increased interest in approaches for creating or maintaining late successional forest characteristics (Franklin et al., 2002). Silvicultural prescriptions on public lands increasingly include the use of extended rotations and the creation of complex stand structures (Kohm and Franklin, 1997; Curtis et al., 1998). These prescriptions often entail performing intermediate treatments in stands middle-aged or older, which until very recently would have been scheduled for regeneration harvest. Managers in the Pacific Northwest region of the United States, and elsewhere, are increasingly implementing these novel silvicultural approaches, generally with imperfect knowledge of expected long-term stand responses. A better understanding of the growth implications of these treatments would aid in designing prescriptions to meet specific objectives.

Several studies have looked at growth of older trees, and their ability to respond to reductions in stocking. Worthington (1966), for example, reported positive tree diameter growth response 30 years after thinning of a 60-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand. However, no diameter growth responses were noted 7 years (Steele, 1948) or 13 years (Steele, 1954) following light thinning in 97-year-old Douglas-fir. Neither Yerkes (1960) nor Williamson (1966) could show individual tree growth responses at 6 or 11 years, respectively, following thinning in a 110-year-old Douglas-fir stand; however, 19 years following the treatment Williamson

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0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2008.01.043

(1982) was able to show a diameter growth response. These studies and others (e.g. Dolph et al., 1995; Latham and Tappeiner, 2002) suggest that several western conifer species may retain the ability to respond to thinning at advanced ages, although growth responses may not become apparent for several years following density reduction.

Projecting growth and yield responses to silvicultural approaches intended to create structural and compositional diversity within stands can present challenges. Many of the models available for projecting growth may not be adequately calibrated for older stands now being managed. In addition, existing models may not adequately project growth of stands with widely variable growth conditions (Monserud and Robinson, 2002). Past growth and yield studies, upon which current models are often based, typically used relatively small plots laid out over areas uniform in site and stand conditions with treatments applied uniformly across the area. Skid trails and landings were generally excluded from study plots. Studies of newer silvicultural approaches are often laid out over larger, more diverse areas; and commonly involve non-uniform treatments across the area (e.g., variable-density thinning). Operationally, skid trails or cable corridors will be present throughout a stand, so it makes little sense to ignore their influence on tree and stand growth response.

One approach to projecting growth of stands treated with prescriptions designed to create spatial diversity would be to model smaller, uniformly treated portions of the stand separately, and aggregate the projected growth responses of each ‘treatment’ based on proportional representation across the stand. For example, if 50% of an area was thinned, 25% was left untreated, and gaps were created on the remaining 25% of the area, then each of the three treatments could be modeled separately and their results aggregated and weighted by the proportion of area occupied by each treatment. That approach, however, ignores potential growth influences resulting from internal edge effects (i.e., differences in density at treatment boundaries).

Another approach to modeling growth of these stands would be to use a spatially explicit model that utilizes information on individual tree locations to examine the competitive environment of each tree. This would allow greater model flexibility to account for the variation in tree growth that occurs due to the structural diversity being created across the stand and the influence of internal edges within the stand. Collection of tree coordinate information is expensive, however; and therefore, its incorporation into growth simulation models can only be justified if it provides significant improvement to growth and yield projections.

A third approach to modeling growth of stands with high spatial diversity would be to model the uniformly treated areas separately, but include modifiers to account for the influence of internal edges on tree growth. This approach would require some spatial information about the layout of various subtreatments, but would not require individual stem coordinates.

The Olympic Habitat Development Study was designed to examine responses of plant and animal communities, tree growth, and stand development following variable-density thinning in 35- to 70-year-old stands on the Olympic Peninsula in Western Washington. Studies to date have involved examinations of small mammals (Carey and Harrington, 2001), understory plant development (Harrington et al., 2005), and wind damage associated with variable-density thinning (Roberts et al., 2007). In this analysis, we examine 5-year individual tree basal area growth response from five stem-mapped plots ranging in age from approximately 40–65 years. Our objectives were to: (1) evaluate factors that influence individual tree growth following variable-density thinning; (2) determine if edge effects associated with the components of variable-density thinning influence individual tree growth; and (3) assess whether incorporation of individual tree local competition indices could account for differences in tree growth associated with treatments and internal edges.

2. Methods

2.1. Site description

Stem-mapped plots from five blocks of the Olympic Habitat Development Study were included in this analysis. All are within the Olympic National Forest located on the Olympic Peninsula in northwestern Washington. Soils at all five blocks are generally deep loams with good drainage. Elevations range from a low of approximately 150 m to a high of nearly 600 m. Winters are generally cool and summers warm, with mean annual temperatures of approximately 9–10 °C. Average annual precipitation ranges from 1450 mm at the lower elevations of the Snow White block, situated in the rain shadow of the Olympic Mountains, to nearly 3200 mm at Bait, the most southwestern block in the study (Table 1). Annual precipitation falls mostly as rain during the winter, with comparatively dry summers.

The Fresca and Rail blocks were regenerated naturally following clearcutting and broadcast burning around 1930, and both still appear as recently cutover in 1939 aerial photography implying a prolonged stand initiation phase. Both blocks are situated on terraces of the Solduc River with generally flat topography. The dominant plant association at Fresca is *Picea sitchensis*/*Oxalis oregana* (Henderson et al., 1989). The current stand is dominated by Sitka spruce (*P. sitchensis* (Bong.) Carr.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Table 2). Site index for both western hemlock and Sitka spruce is ca. 37 m at 50 years (Wiley, 1978; Farr, 1984). No known silvicultural treatments had occurred at Fresca prior to the present study. Rail is dominated by the *T. heterophylla*/*Gaultheria shallon–Polystichum munitum* plant association (Henderson et al., 1989). The current stand consists almost entirely of western hemlock and Douglas-fir (*P. menziesii* (Mirb.) Franco) (Table 2). Site indices at 50 years for western hemlock and Douglas-fir are ca. 41 and 38 m, respectively (Wiley, 1978; King, 1966). A light salvage thinning was conducted at Rail in 1986, removing less than 15% of the stocking.

Bait was clearcut in the early 1950s, and likely burned prior to being planted with Douglas-fir. Substantial amounts of western

Table 1
Site description for five stem-mapped plots located on the Olympic National Forest that were examined for tree growth response to variable-density thinning

Block	BH Age[a] (years)	Elevation (m)	Annual precip. (mm)	Avg. temp.[b] (°C)	Soils	Primary tree species
Fresca	50	150	2650	10, 23, 1	Silt loam, very deep, well drained, from glacial outwash Emmiott series (Medial, ferrihydritic, isomesic Eutric Pachic Fulvudands)	Western hemlock, Sitka spruce
Rail	43	275	2390	9, 23, 0	Loam/sandy loam, very deep, well to somewhat excessively drained, from glacial outwash, Bogachiel–Ishmael complex (mesic Typic Udivitrands)	Douglas-fir, western hemlock
Bait	38	245	3175	9, 22, 1	Silt loam, very deep, somewhat poorly to moderately well drained, formed in residuum and colluvium, Thimblepeak–Haas complex (Alic Epiaquands)	Western hemlock, Douglas-fir
Snow White	63	580	1955	8, 23, −1	Sandy loam, moderate deep, moderately well drained, from glacial till, Rockybrook series (Loamy-skeletal, isotic, frigid Andic Dystrudepts)	Douglas-fir, western hemlock, western redcedar
Clavicle	48	475	2360	9, 22, 1	Silt loam, deep, moderately well drained, from loess and ablation till, Ozette series (Medial, ferrihydritic, isomesic Aquic Fulvudands)	Western hemlock, Sitka spruce

[a] Breast height age based on 6–10 dominant trees.

[b] Average temperatures provided as mean annual, mean August maximum, and mean January minimum based on PRISM model values (model description in Daly et al., 1994; USDA, 1999; data available from http://prism.oregonstate.edu/).

hemlock has established naturally. Slopes range from 0% (hilltops) to 35%. The predominant plant associations are *T. heterophylla*/*P. munitum*–*O. oregana* and *T. heterophylla*/*G. shallon*–*O. oregana*. The current stand consists almost entirely of Douglas-fir and western hemlock (Table 2). Site index at 50 years for both species is ca. 40 m. Bait received a light pre-commercial thinning in the late 1960s and early 1970s. There are no records of the stand receiving any other cultural treatments.

Snow White is the only block located on the east side of the Olympic Peninsula. The site was clearcut around 1928, burned, and planted with Douglas-fir in the early 1930s. Slopes at Snow White generally vary from 10 to 25%. Common plant associations include *T. heterophylla*/*Mahonia repens*/*O. oregano*, *T. heterophylla*/*G. shallon*/*P. munitum*, and *T. heterophylla*/*G. shallon*. The current stand is dominated by Douglas-fir, with substantial components of western hemlock and

Table 2
Species composition prior to, and immediately following, application of the variable-density thinning treatment for the five stem-mapped plots on the Olympic National Forest

	Pre-harvest			Post-harvest		
	Density (tph)	D_Q[a] (cm)	Mean Ht[b] (m)	Density (tph)	D_Q[a] (cm)	Mean Ht[b] (m)
Fresca						
Sitka spruce	153	51.6	37.7	120	54.2	38.5
Western hemlock	278	38.1	30.1	171	41.0	31.0
Other	28	40.3	28.8	26	41.3	28.4
Rail						
Douglas-fir	263	42.6	34.7	207	45.0	35.8
Western hemlock	139	33.8	30.0	96	36.0	31.0
Bait						
Douglas-fir	474	36.1	32.0	288	39.5	33.3
Western hemlock	350	27.2	26.4	207	29.7	27.4
Sitka spruce	1	26.0	30.0	1	26.4	30.1
Snow White						
Douglas-fir	268	45.2	35.3	194	49.3	36.9
Western hemlock	120	24.9	21.1	90	24.2	19.5
Western Redcedar	70	24.5	16.6	61	26.0	17.3
Red Alder	35	13.0	12.3	2	14.6	13.2
Clavicle						
Sitka spruce	193	54.8	38.6	153	58.2	39.6
Western hemlock	458	32.1	30.3	217	35.5	31.9
Other	27	35.8	26.2	17	39.1	26.4

Data do not include understory trees.

[a] Quadratic mean diameter.

[b] Mean height calculated from predicted heights. Actual height measurements were taken on a subset of live trees.

western redcedar (*Thuja plicata* Donn ex D. Don) (Table 2). Site index at 50 years for Douglas-fir is ca. 35 m. The site was commercially thinned in the early 1970s.

Clavicle is shown on forest inventories as recently cutover in the early 1930s. Typical management in the area at that time following logging involved burning of slash and allowing the site to regenerate naturally. Breast height age in 1994 was only 48 years, which suggests the area endured an extended or delayed period of stand establishment. The area of the stand examined in this study sits on a flat ridge with slopes generally less than 5%. The predominant plant association at Clavicle is *P. sitchensis*/*P. munitum*/*O. oregana*. The current stand is dominated by western hemlock and Sitka spruce. Site index at 50 years for western hemlock is ca. 35 m, and for Sitka spruce is ca. 39 m. There are no records of any management activities in the stand prior to the present study.

2.2. Treatments

A variable-density thinning was implemented at Fresca and Rail in 1997 and at Bait, Snow White, and Clavicle in 1999. The prescription called for a series of gaps and untreated patches to be embedded within a uniformly thinned matrix. Creation of 0.04–0.05 ha gaps over 15% of the treatment area involved removal of all merchantable stems (>ca. 20 cm dbh) with the exception of species of low local abundance (e.g., hardwoods, western redcedar). Unthinned patches were 0.1–0.3 ha in size scattered over 10% of the treatment area. No harvest or entry of equipment was allowed in the unthinned areas. The thinned matrix, covering the remaining 75% of the treatment area, called for 25% basal area removal, primarily from the lower crown classes. All trees were hand felled. Ground-based yarding equipment was used to remove trees in all blocks except Bait, which used a skyline yarding system. Yarding equipment was restricted to designated skid trails. There was little apparent difference in skid trail width (approximately 3 m) or logging impacts among the blocks.

Treatment areas within each block were approximately 10 ha in size, and replicated three or four times within each block. Within one of the treatment areas in each block, a single plot of 1.44 ha (1.53 ha at Fresca) was established for complete stem mapping. Each stem-mapped plot contained two complete gaps, one complete unthinned patch, and a portion of a third gap and second unthinned patch. Within the plot, all trees greater than 1.3 m tall were tagged and their coordinates stored in a GIS database. Treatment (gap, unthinned, thinned matrix) boundaries and skid trails used in the harvest operations were also mapped. A summary of stand conditions prior to, and immediately following, the variable-density thinning is provided in Table 3.

Table 3
Stand conditions prior to, and immediately following, application of the variable-density thinning treatment at five sites (blocks) on the Olympic National Forest

	Density (tph)	D_Q (cm)	Mean Ht[a] (m)	BA ($m^2\ ha^{-1}$)	SDI[b]	RD[c]
Fresca						
Pre-harvest	459	43.2	32.5	67.4	1104	71
Post-harvest	317	46.4	33.6	53.7		
Gap	25	18.5	15.5	0.7	15	1
Unthinned	526	43.4	33.7	77.8	1273	82
Thinned	296	47.6	33.7	52.6	830	53
Rail						
Pre-harvest	401	39.8	33.1	50.0	846	55
Post-harvest	303	42.4	34.3	42.7		
Gap	20	12.9	12.9	0.3	7	1
Unthinned	450	40.2	33.7	57.2	964	63
Thinned	281	43.6	34.7	42.1	687	44
Bait						
Pre-harvest	826	32.6	29.6	69.1	1265	84
Post-harvest	496	35.7	30.8	49.7		
Gap	63	38.7	29.2	7.4	126	8
Unthinned	767	33.9	30.4	69.2	1249	82
Thinned	433	36.8	31.2	46.0	804	53
Snow White						
Pre-harvest	493	36.9	27.6	52.7	920	60
Post-harvest	347	40.4	28.8	44.5		
Gap	125	25.7	16.9	6.5	131	9
Unthinned	444	40.8	30.3	58.0	973	63
Thinned	333	40.5	28.5	42.9	722	47
Clavicle						
Pre-harvest	678	40.1	32.5	85.6	1445	94
Post-harvest	388	45.9	34.7	64.2		
Gap	25	37.4	29.1	2.3	48	3
Unthinned	687	39.9	32.8	86.1	1455	94
Thinned	351	48.2	35.5	64.1	1006	64

Data do not include understory trees.

[a] Mean height calculated from predicted heights. Actual height measurements were taken on a subset of live trees.

[b] SDI = $(D_Q/25)^{1.605}$ × TPH (Reineke, 1933). Maximum SDI for hemlock and spruce assumed to be 1950, and for Douglas-fir assumed to be 1450 (Long, 1985).

[c] Relative density (RD) = $BA/D_Q^{0.5}$ (Curtis, 1982)—metric measures of BA and D_Q were converted to English units.

2.3. Field measurements and data development

Detailed measurements were taken within each stem-mapped plot before and after the variable-density thinning treatment, and again after the fifth growing season following treatment. Diameter at breast height (dbh, 1.3 m) was measured for all tagged trees, and species, crown class, and damage were recorded. Total height and height to base of live crown were taken on a subsample of between 75 and 143 trees per stem-mapped plot. Basal area (BA) of each tagged tree was calculated immediately after thinning and 5-years post-treatment. A 5-year BA increment was calculated for each tree as the difference between the two post-treatment measurements.

Trees in proximity to treatment edges within the stem-mapped plots were identified in the GIS database. These included trees in the thinned matrix within 10 m of a gap and within 10 m of an unthinned patch, and trees in the unthinned area within 10 m of the thinned matrix. In addition, trees in the thinned matrix within 3 m of a skid trail were identified. Proximity to edges was treated as a class variable, i.e., trees were either within 10 m of the edge (3 m for skid trails) or they were not.

A 10-m radius competition plot centered on the subject tree was established for all trees greater than 10 m from the outer stem-mapped plot boundary. Indices of local competition were calculated for each tree. Four of these indices were distance-independent—their calculation does not depend on the distance between the subject tree and individual competitors. These indices were:

BAT = the sum of the basal area of all trees within a 10-m radius circle centered on the subject tree, including the BA of the subject tree.

BAC = the sum of the basal area of all competitor trees within a 10-m radius circle centered on the subject tree, *not* including the BA of the subject tree.

BAL = the sum of the basal area of all competitor trees within a 10-m radius circle centered on the subject tree, whose dbh was larger than that of the subject tree.

RDC = relative density of competitors—an index of the relative density of all trees within a 10-m radius circle centered on the subject tree, not including the subject tree (based on Reineke's (1933) stand density index).

Four distance-dependent indices, all permutations of an inverse distance-weighted competition index (*sensu* Hegyi, 1974) were also calculated for each tree. These indices implicitly assume that larger trees are stronger competitors than smaller trees, and trees closer to the subject tree are stronger competitors than trees farther away. The distance-dependent indices were:

$CI_1 = \Sigma(d/D)/\mathrm{DIST}$

$CI_2 = \Sigma(d/D)/(\mathrm{DIST}^2)$

$CI_3 = \Sigma(d/D)^2/\mathrm{DIST}$

$CI_4 = \Sigma(d/D)/\mathrm{DIST}$ (for competing trees larger than the subject tree, i.e., $d > D$)

where D = dbh of subject tree, d = dbh of competing trees within a 10-m radius of subject tree, and DIST = distance between subject tree and competing tree.

Daniels et al. (1986) recommend using a variable-radius plot centered on the subject tree with a limiting distance determined by the size of the competitor. Given the size of the larger trees on our plots, this would have required either compensating for edge bias for many trees (Radke and Burkhart, 1998) or providing a buffer inside the outer boundary of the stem-mapped plot so large that it would have greatly reduced the number of trees in the analysis. While variable-radius plots may be desirable, fixed-radius plot have been successfully used. Hegyi (1974) used 3-m radius plots in his examination of competition in jack pine (*Pinus banksiana* Lamb.). Mailly et al. (2003) used 4-m radius plots in their study of competition in mature, uneven-aged black spruce (*Picea mariana* (Mill.) B.S.P.). Our competition plot size (10-m radius) was a compromise between large variable-radius plots and the small fixed-radius plots used in previous studies.

Only eight competition indices were examined in this study, although numerous other indices have been proposed and evaluated by others (e.g., Daniels et al., 1986; Tomé and Burkhart, 1989; Biging and Dobbertin, 1992, 1995). Our intention was not to determine which local competition index was best, but rather to examine whether competition indices, in general, might be useful tools in modeling the growth of trees in complex stand structures.

2.4. Analysis

A total of 2597 trees were included in the analysis—1141 western hemlock, 965 Douglas-fir, 389 Sitka spruce, and 102 western redcedar. Species present in only one block (e.g., Pacific silver (*Abies amabilis* Dougl. ex Forbes) fir at Bait) or those with insufficient numbers to represent the different treatment categories across blocks were not included in the analysis. Only trees alive at both the beginning and end of the 5-year growth period were included. Understory trees identified as relatively recent advanced regeneration were excluded.

An exploratory analysis indicated that the relationship between 5-year basal area growth and initial tree size (dbh immediately post-treatment) was nonlinear, and that the relationship varied with both species and crown class. Examination of scatter plots and analysis of residuals indicated that the square root of 5-year basal area increment ($\sqrt{\mathrm{BAI}_5}$) provided the best linear fit with dbh (unbiased residuals, homogeneity of variance) across species and crown classes. Approximately 1% of the trees had slightly negative calculated growth rates, most likely due to normal imprecision associated with field measurements. To facilitate use of the square root transformation, a constant was added to the 5-year basal area growth increment of each tree in order to bring the minimum basal area growth value to approximately 1.0 (Osborne, 2002).

Analysis of covariance was used to test for significant impacts on $\sqrt{\mathrm{BAI}_5}$ of individual trees using the GLM procedure in SAS (SAS Institute Inc., Cary, NC, release 9.1.3). A critical value of $\alpha = 0.10$ was used in all analyses for determining significance. This critical value was chosen to compensate for the generally lower statistical power of field studies (Peterman, 1990). In addition, with the relatively short response period (5 years) we felt the higher critical value was more appropriate given that stands of this age are often slow to respond to treatments. The relative importance of a given variable in the model was evaluated by examining the percent reduction in mean squared error (MSE) relative to models not containing the variable (Biging and Dobbertin, 1995; Mailly et al., 2003).

With block, species, initial tree size, and crown class in the model, treatment (thinned matrix vs. unthinned patch) was included as a covariate to test for treatment effects on $\sqrt{\mathrm{BAI}_5}$. We also examined whether the growth of trees near skid trails or treatment boundaries was affected by their proximity to these edges. Indicator variables, which signified whether trees were within 3 m of a skid trail or within 10 m of a treatment boundary, were included in the model to determine if they were effective in explaining variability in $\sqrt{\mathrm{BAI}_5}$.

Finally, we tested whether local competition indices were significant in explaining variability in $\sqrt{\mathrm{BAI}_5}$, and whether their inclusion in the model accounted for significant treatment or edge effects. Competition indices were tested alone to

Table 4
Average initial stem diameter at breast height (immediately post-treatment), 5-year radial increment, and 5-year basal area increment for 2597 trees included in tree growth analysis at study sites on the Olympic National Forest

	n	Diameter breast height (1.3 m) (cm)	Five-year diameter increment (cm)	Five-year basal area increment (cm^2)
All Trees	2597	38.8	2.0	142
Fresca	407	45.4	2.1	180
Rail	422	41.5	2.3	163
Bait	667	34.6	1.8	109
Snow White	575	32.2	1.9	116
Clavicle	526	44.1	2.0	165
Western hemlock	1141	30.9	1.7	94
Douglas-fir	965	43.3	2.0	149
Sitka spruce	389	55.2	2.9	281
Western redcedar	102	22.7	1.7	76

determine if they were significantly correlated with $\sqrt{\mathrm{BAI}_5}$. The indices were then included in the model containing block, species, initial tree size, crown class, and treatment. Where significant edge effects were identified, competition indices were included in a model containing the edge variable.

3. Results

The average dbh of the trees included in the analysis was 39.0 cm, with trees ranging in size from 3.2 to 99.4 cm. Five-year radial increment averaged 1.3 cm (−0.9 to 7.5 cm), and 5-year BA increment averaged approximately 142 cm^2 per tree (−39.3 to 991 cm^2) (Table 4). Block, species, initial tree size, and crown class were all significant ($P < 0.001$) when examined independently. In combination they explained approximately 69% of the variability in $\sqrt{\mathrm{BAI}_5}$.

Of the 2597 trees included in the analysis, 1818 were in the thinned matrix of the stem-mapped plots and 779 were in the unthinned areas. With block, species, initial tree size, and crown class in the model, treatment increased the amount of variation in $\sqrt{\mathrm{BAI}_5}$ explained to nearly 71% and reduced MSE by 4% (Table 5). Treatment was significant when examined at all five blocks individually ($P < 0.001$), with growth increases due to thinning ranging from 15% at Rail to over 30% at Fresca and Clavicle. Overall, the average BA growth in the thinned matrix was almost 26% greater than in the unthinned areas when adjusted for block, species, initial size, and crown class (Fig. 1).

Proximity to internal edges did influence individual tree BA growth. With block, species, initial tree size, and crown class in the model, the adjusted average $\sqrt{\mathrm{BAI}_5}$ of trees within 10 m of gap edges was nearly 11% greater than that of trees in the thinned matrix farther away from the gaps (Fig. 2); although accounting for proximity to gap edges reduced MSE by only 0.8% (Table 5). The increased basal area growth due to being close to a gap was also affected by which side of the gap a tree was located. Trees on the north side of a gap averaged 21% greater basal area growth than trees on the south side of gaps and about 15% greater than growth of trees on the east and west sides of gaps.

Skid trails also appeared to influence tree growth. The adjusted average growth of trees within 3 m of a skid trail was ca. 11% greater than that of trees in the thinned matrix farther from skid trails (Fig. 2); but including proximity to skid trails in the model only reduced MSE by about 0.6% (Table 5).

Growth of trees in the thinned matrix within 10 m of an unthinned patch did not differ significantly from that of trees farther from the edge (Table 5), although on average the growth of trees closer to the unthinned edge was about 3% lower

Table 5
Improvements in model explaining $\sqrt{\mathrm{BAI}_5}$ resulting from adding treatment or proximity to internal edges to the base model containing block, species (spp), initial dbh, and crown class (cc)

Model and model variables	n[a]	r^2	MSE	% MSE reduced[b]
Base model I				
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc	2597	0.69	6.40	
Enhanced model				
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat	2597	0.71	6.15	4.0
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, gap <10 m	1062	0.72	6.17	0.8
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, skid trail <3 m	977	0.71	6.32	0.6
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, skip <10 m	1192	**	**	
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, thin <10 m	779	**	**	

** Indicates variable added to the base model is not significant.

[a] The number of trees included in the enhanced models evaluating edge effects is a subset of the trees in the overall analysis. Subsetting of the data eliminated trees from other treatments and within edges other than the edge being analyzed.

[b] Percent MSE reduction is relative to the base model containing the same subset of trees as the specific enhanced model.

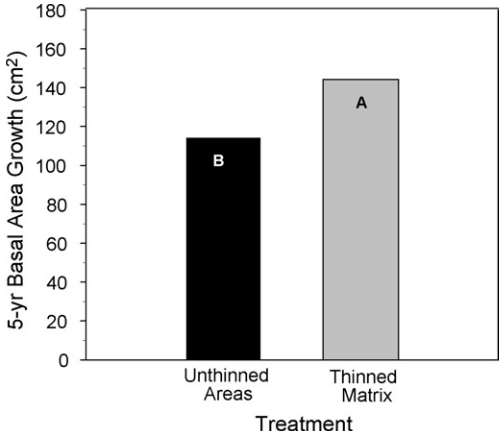

Fig. 1. Average 5-year basal area growth for canopy trees within thinned and unthinned treatments across five sites on the Olympic Peninsula. Bars with different letters indicate statistically significant differences in growth between treatments at the site (t-test, $\alpha = 0.10$). Mean values are adjusted least squared means from a model that included block, species, crown class and initial tree size.

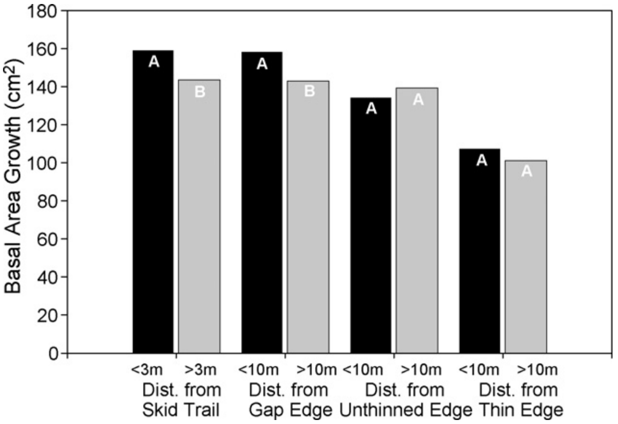

Fig. 2. Edge effects on average 5-year basal area growth for canopy trees across five sites on the Olympic Peninsula. Bars with different letters indicate statistically significant differences in growth between trees in close proximity to edges compared to trees farther from edges (t-test, $\alpha = 0.10$). Mean values are adjusted least squared means from a model that included block, species, crown class and initial tree size.

(Fig. 2). Within the unthinned patches, the growth of trees within 10 m of the thinned edge averaged about 6% greater than trees farther from the edge; but again these differences were not significant (Table 5, Fig. 2).

The local competition indices were tested individually to see how well they correlated with tree growth. All indices were significantly correlated with $\sqrt{\mathrm{BAI}_5}$, with all but one (CI_2) having a P-value < 0.001. The amount of variability in $\sqrt{\mathrm{BAI}_5}$ explained by the indices ranged from <1% to 40%. BAL, the basal area of trees within a 10-m radius and larger in diameter than the subject tree, had the strongest correlation with BA growth. When local competition indices were included in the model with block, species, initial tree size, and crown class, all of the distance-independent indices remained significant, but among the distance-dependent indices CI_2 and CI_4 were not significant (Table 6). The reduction in MSE for the significant indices ranged from 0.1% to nearly 4%. The index performing best in this model was again BAL.

Table 6
Improvements in model explaining $\sqrt{\mathrm{BAI}_5}$ resulting from adding local competition indices to (a) base model containing block, species (spp), initial dbh, and crown class (cc), and (b) base model containing block, species, initial dbh, crown class, and treatment

Model and model variables	r^2	MSE	% MSE reduced
(a) Base model I			
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc	0.69	6.57	
Enhanced model			
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, BAT	0.69	6.39	2.7
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, BAC	0.69	6.39	2.8
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, BAL	0.70	6.32	3.8
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, SDI	0.69	6.40	2.6
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, CI_1	0.69	6.57	0.1
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, CI_2	**	**	
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, CI_3	0.69	6.53	0.7
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, CI_4	**	**	
(b) Base model II			
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat	0.70	6.31	
Enhanced model			
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, BAT	0.70	6.28	0.5
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, BAC	0.70	6.27	0.6
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, BAL	0.70	6.17	2.2
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, SDI	0.70	6.29	0.4
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, CI_1	0.70	6.29	0.3
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, CI_2	**	**	
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, CI_3	0.70	6.27	0.6
$\sqrt{\mathrm{BAI}_5}$ = block, spp, dbh, cc, treat, CI_4	**	**	

The 1856 trees in this analysis do not include trees in the 10 m buffer around the outer edge of the stem-mapped plots.
** Indicates variable added to the base model is not significant.

All of the distance-independent competition indices along with CI_1 and CI_3 remained significant when treatment was included in the model (Table 6). Again, BAL performed best in this model, reducing MSE by 2.2%. None of the indices, however, fully accounted for the significant treatment effect on BA growth; i.e., treatment remained significant when competition indices were added to the model. In no case did a model which included a competition index but without treatment perform better (i.e., lower MSE) than the model that included treatment but no local competition index (Table 6).

Six of the eight competition indices remained significant when included in the model containing block, species, initial tree size, crown class, and the significant edge effects (proximity to gaps and to skid trails). Again, however, the edge effects remained significant in the models with the competition indices. When models that explicitly recognized proximity to internal edges were compared to models that utilized the local competition indices, the local competition indices generally performed as well as, and sometimes better than, explicitly identifying trees close to skid trails. BAL performed best among the indices, resulting in 2.6% greater reduction in MSE than the model which accounted for trees within 3 m of the trails. For trees close to gap edges, the local competition indices generally did not perform as well as models that explicitly recognized trees within 10 m of a gap, with the exception of BAL which again resulted in about 1% lower MSE than did models accounting for proximity to the gap edge.

Across individual study blocks, the effects of gap edges on basal area growth ranged from less than 6% to over 24% while the influence of skid trails ranged from a nearly 7% decrease to almost 38% increase in basal area growth of adjacent trees. One factor that appears to have influenced the magnitude of observed edge effects was pretreatment stand history and the effect it had on initial stand conditions. Two of the blocks, Rail and Snow White, had received earlier commercial thinnings resulting in lower initial stocking rates at the beginning of this study. Stand density index (SDI; Reineke, 1933) values for the three blocks that had not been previously thinned averaged over 1270 compared to an average SDI of 883 for the two previously thinned blocks. In addition, the percentage of stocking removed from the thinned matrix during the variable-density thinning averaged over 30% in the three blocks that had not been previously thinned compared to average removals of approximately 20% from the previously thinned blocks.

Stand history (previously thinned vs. unthinned) was significant ($P < 0.001$) when substituted for block in the model testing for overall treatment effects on basal area growth. Average basal area growth of trees in the previously thinned blocks, adjusted for species, crown class, and treatment, was around 30% greater than that of trees in the blocks that had not been previously thinned, reflecting the lower stocking in these stands. However, despite greater absolute tree growth rates, basal area growth gains associated with gap edges in the previously thinned blocks averaged less than 6% compared to nearly 16% in the previously unthinned blocks (Fig. 3(top)). The growth gains associated with skid trails in the previously thinned blocks averaged less than 2% while the gain in the previously unthinned blocks averaged over 24% (Fig. 3(bottom)).

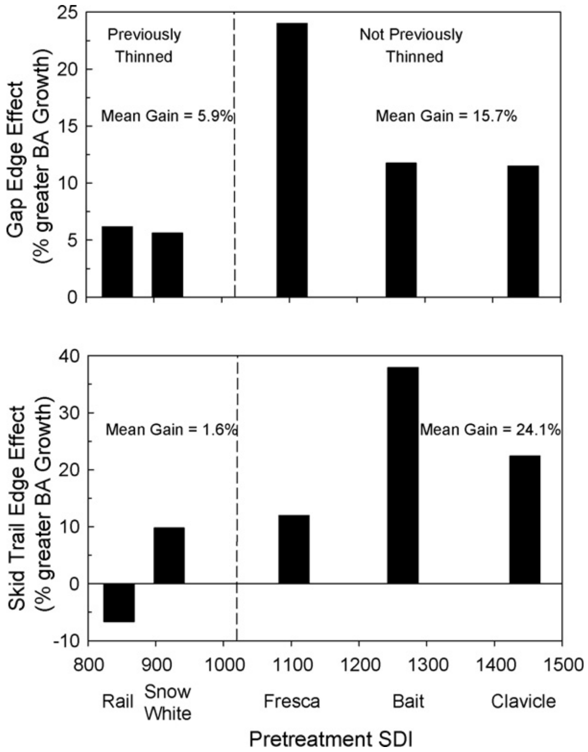

Fig. 3. The influence of pretreatment stocking levels and prior commercial thinning on basal area growth gains resulting from edges associated with canopy gaps (top) and skid trails (bottom) at five sites on the Olympic Peninsula receiving a variable-density thinning.

4. Discussion

The variable-density thinning treatment employed in this study was relatively light, removing only 20–30% of existing basal area from the thinned matrix. Even so, significant growth responses occurred in all five blocks 5 years following treatment. That we were able to observe growth responses in stands this old was not surprising. Several studies have shown that stands in the Pacific Northwest region much older than the stands in this study will respond to thinning (Worthington, 1966; Williamson, 1982; Latham and Tappeiner, 2002). Somewhat surprising was that the growth response was observed so quickly, particularly since relative densities of the stands following treatment remained fairly high (Table 3).

The models we tested were successful in explaining much of the variability in individual tree basal area growth. Block, species, initial tree size, and crown class together explained nearly 70% of the variation in $\sqrt{BAI_5}$. As expected, treatment had a significant influence on tree growth. Explicitly recognizing treatment in the model resulted in an additional 4% reduction in MSE.

The variable-density thinning implemented in this study created internal edges between the gaps, thinned areas, and unthinned patches—edges that potentially influence tree growth. As expected, trees adjacent to gaps took advantage of the nearby available growing space and grew more than trees farther from the gaps. Across the five blocks, local competition experienced by trees near gaps, as measured by the distance-independent competition indices, averaged about 15% less than the competition on trees farther from gaps. The direction of trees from the gap also influenced the growth response, with trees on the north side of the gaps showing the greatest response; although, there were no direction-related differences in the levels of local competition experienced by trees surrounding the gaps.

The average basal area growth of trees in the thinned matrix adjacent to unthinned patches was slightly less than that of trees farther from the edge, although these differences were not significant. Distance-independent indices of local competition for trees close to the edge of the unthinned patch were on average about 10–13% higher than for trees farther from the edge. Within the unthinned patches, proximity to the thinning boundary did not significantly affect tree growth, and distance-independent local competition indices did not differ between trees close to the thinning boundary and those farther from the edge.

Somewhat interestingly, we found skid trails to have a positive effect on basal area growth of adjacent trees. Disturbance associated with skid trails is often, but not always, reported to negatively impact stand productivity (Grigal, 2000; Heninger et al., 2002); although most studies have assessed growth of regeneration rather than older trees. In addition, our study was assessing growth of trees adjacent to rather than on skid trails. One common concern with skid trails is the potential for root damage to trees near the trails, particularly with shallow-rooted species such as Sitka spruce. However, on the deep, moderately well drained soils found on our study sites, root damage was probably minimal. Apparent logging damage other than minor bark abrasion was generally light throughout the study (less than 5%) with the exception of Clavicle which had logging damage on over 10% of residual stems. Grigal (2000) suggested that growth of trees adjacent to roads can benefit from reduced competition. In our study, distance-independent local competition indices for trees adjacent to skid trails averaged about 16–18% lower than for trees farther from the trails, and was likely the major reason for the increased growth.

Individual tree local competition indices were significantly related to basal area growth. However, while inclusion of the indices in the model reduced prediction errors slightly, none of the indices resulted in the treatment effect becoming non-significant. When competition indices were included in the model along with treatment, MSE values were only reduced by an additional 0.2–2.2%. In no case did including a competition index in the model without treatment result in better model performance than simply including treatment in the model without accounting for local competition. Although local competition indices can account for a small amount of additional variation in growth not captured by the treatment effect, our results found that explicitly recognizing local competition did not fully account for the growth responses resulting from the thinning treatment.

Explicitly recognizing local competition also did not fully account for significant edge effects associated with gaps and skid trails. However, even with the significant edge effects (proximity to either gap boundaries or skid trails) retained in the model, six of the eight indices were significant. Adding the index BAL to models that included proximity to gap edges and skid trails reduced MSE by an additional 2.5–2.7% but the other competition indices only reduced MSE by less than 1%. Models that included BAL but did not include the edge variables actually performed better than the models that explicitly accounted for the edge effects, although the other competition indices did not. This suggests at least the potential for using an appropriate competition index to address variations in competition levels resulting from variable-density thinning prescriptions.

Our results suggest that failure to account for internal edge effects associated with treatments and skid trails could affect projections of future stand growth following variable-density thinning. How much difference the failure to account for edge effects makes would depend largely on the size and shape of the patches (gaps and unthinned areas), as these affect the length of edge, and the proportion of the stand in these patches. For example, if we assume a 10-m wide zone of influence for treatment edges, as we did in this study, then a 0.05-ha circular patch would have an edge effect on an area of adjacent forest 2.2 times the patch size. A 0.50-ha circular patch would have an edge effect on an area of adjacent forest only 0.6 times the patch size.

To examine the potential consequences of failing to account for edge effects, let us assume that a growth model is adequately calibrated for species and initial tree size (and perhaps crown class). Further, let us assume that the growth model includes an added growth response to thinning, as some contemporary growth models do (e.g., Hann et al., 2003). Given the magnitude of the significant edge effects detected in this study, if a silvicultural prescription calls for 10% of the stand area in 0.1-ha gaps with the remainder of the stand uniformly thinned, then basal area growth projections in the thinned area would be underestimated by about 2–4% (Table 7). If the gaps were reduced to 0.05 ha in size then growth underestimation would increase to 3–5%. If gaps 0.05 ha in size were scattered over 15% of the stand then growth underestimation would increase to 5–7%. If 25% of the stand was treated with 0.05-ha gaps, growth could be underestimated by as much as 10% (Table 7). This example does not include possible edge effects

Table 7
Potential estimation errors in basal area growth within the thinned matrix resulting from failure to account for internal treatment edge effects

Gap size (ha)	Proportion of stand area in gaps (%)	Error in BA growth projection for thinned matrix	
		No skid trails (%)	With skid trails (%)
0.10	10	−2.1	−3.8
0.05	10	−3.3	−4.9
0.05	15	−4.9	−6.5
0.05	25	−8.1	−9.8

Errors are based on average growth underestimates of 11% for trees within 10 m of gaps and within 3 m of skid trails. "No skid trails" ignores the potential influence of skid trails on tree growth. "With skid trails" assumes that 15% of the thinned area not otherwise affected by treatment patches is influenced by skid trails.

associated with unthinned patches which were not significant in our study.

The implications of not accounting for edge effects on growth can be quite variable as illustrated by the fourfold difference in growth response to gap edges among our five blocks. The growth response to skid trail edges was even more variable. One factor that appears to have influenced the observed growth responses was pretreatment stand history and the effect it had on initial stand conditions. The two blocks that had previously been thinned, on average, displayed lower positive growth responses to the gap and skid trail edges created as part of the variable-density thinning. This study, while not specifically designed to test the effects of stand history and pretreatment stand densities on individual tree growth, certainly suggests that stand history and initial stand conditions could influence the edge effect response. The differential responses we observed across blocks, however, might also have been due to differences in thinning intensities associated with the variable-density thinning, which were only indirectly correlated with the stand histories.

Whether improvements in growth projections resulting from explicitly accounting for internal edge effects would justify the added expense and complexity of requiring spatially explicit data would certainly depend on the magnitudes of the edge effects. Clearly, however, failure to account for edge effects on tree growth, where present, could in some situations effect future stand growth projections, as our examples illustrate (Table 7). New modeling approaches may need to be developed which minimize model complexity while approximating the spatial variability occurring in stands treated with variable-density thinning operations.

Failure to recognize edge effects, as well as other growth-related factors influenced by the creation of spatial diversity, could have additional implications beyond just growth and yield estimation. An objective of variable-density thinning is often to promote future size-class diversity within a stand. Enhanced growth of trees near gaps and skid trails and reduced growth near unthinned patches will accelerate size class differentiation, and thus promote development of structural diversity. Failure to recognize differences in growth rates of trees near edges would make it more difficult for growth and yield models to assist in determining if prescriptions are likely to meet long-term stand structural objectives.

Our analysis was not intended to be a definitive study of the growth and yield implications of variable-density thinning. Rather, our results indicate that internal edges created through variable-density thinning can significantly affect individual tree growth, although the magnitude of the effect varied widely across individual blocks due to differences in species composition, stand histories, and site conditions. This analysis also suggests that stands with higher levels of stocking prior to treatment are likely to display greater edge effects.

We caution against attempts to extend the results of this study too widely. Our goal was to identify potential issues surrounding the projection of growth following variable-density thinning or similar prescriptions that create internal edges within stands. Growth analysis of nearly 2600 trees from our five blocks clearly illustrates the potential effects that internal edges can have on growth of adjacent trees. The structural diversity being sought in many silvicultural prescriptions presents challenges for model developers and managers attempting to project growth. Additional studies will be needed to determine when and where it is reasonable to expect edge effects on tree growth, and the timing and duration of these effects. Further work will be required to develop efficient modeling approaches for addressing these issues.

Acknowledgements

We thank the Olympic National Forest for implementing the treatments, and the Pacific Northwest Research Station Wood Compatibility Initiative for supporting the establishment and initial measurement of the stem-mapped plots. We also thank Drs. Robert Curtis, David Marshall, Daniel Gilmore, and Peter Gould for helpful comments on earlier drafts of this manuscript. This manuscript was approved for publication as Journal Article FO-358 of the Forest and Wildlife Research Center, Mississippi State University.

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