Growth responses to commercial thinning in Douglas-fir stands with varying severity of Swiss needle cast in Oregon, USA

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Abstract: Concern has risen about the degree to which Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands with severe infections of Swiss needle cast (SNC) respond to thinning. A retrospective study was established in the fall of 2001 to assess the growth of Douglas-fir stands that were commercially thinned between 4 and 10 years ago. Current SNC infection levels in these stands ranged from severe to very light. Past volume and basal area growth declined with increasing severity of SNC, as measured by current foliage retention and crown length / sapwood ratio. As has been observed in many other studies, thinning to lower residual stock reduced stand level growth; however, individual tree growth increased with lower residual stand density. The ratio of growth in successive periods and analysis of annual basal area growth since thinning suggested that trees did respond to thinning, although less so as SNC increased. A positive response to thinning, regardless of infection level, was confirmed by an analysis of annual trends in basal area growth over the first 5 years after thinning.

Résumé : On s'interroge de plus en plus sur la capacité des peuplements de douglas (*Pseudotsuga menziesii* (Mirb.) Franco) sévèrement infectés par la rouille suisse de réagir à une éclaircie. Une étude rétrospective a été établie à l'automne 2001 pour évaluer la croissance des peuplements de douglas qui ont subi une éclaircie commerciale depuis 4 à 10 ans. La situation présente de la rouille suisse dans ces peuplements varie de sévère à très légère. La croissance passée en volume et en surface terrière, mesurée par la rétention du feuillage courant et le rapport de la hauteur de cime sur le bois d'aubier, a diminué avec l'augmentation de la sévérité de la rouille suisse. Tel qu'il a été observé dans plusieurs autres études, éclaircir pour diminuer le volume résiduel réduit la croissance du peuplement. Cependant, la croissance des arbres pris individuellement augmente avec une densité résiduelle plus faible du peuplement. Le ratio de croissance au cours de périodes successives et l'analyse de la croissance annuelle en surface terrière depuis l'éclaircie indiquent que les arbres ont réagi à l'éclaircie bien que moins fortement à mesure que la rouille suisse progresse. Une réaction positive à l'éclaircie, peu importe le niveau d'infection, a été confirmée par les tendances annuelles de la croissance en surface terrière au cours des cinq premières années après l'éclaircie.

[Traduit par la Rédaction]

Introduction

Many Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands in western Oregon are suffering from Swiss needle cast (SNC), a foliage disease caused by the fungus *Phaeocryptopus gaeumannii* (Rohde) Petrak (Hansen et al. 2000). Although this fungus is endemic throughout the range of coastal Douglas-fir (Boyce 1940), there have been noted increases in fungal presence, infection incidence, disease symptoms, and associated negative growth responses in the last 10 years (Hansen et al. 2000). A recent aerial survey indicated that approximately 71 000 ha of the 950 000 ha surveyed in Oregon showed detectable discoloration, a decrease from a high of 157 000 ha in 2002 (Kanaskie et al. 2004).

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Of greatest concern are the approximately 76 000 ha of 10- to 30-year-old plantations in north coastal Oregon. These plantations exhibit varying degrees of SNC severity, but severe SNC infection may prevent them from attaining merchantable size. Stands with the most severe SNC were experiencing a volume growth loss of approximately 52% from 2000 to 2002, with a population average of 21% from 2000 through 2002 (Maguire et al. 2002). Some severely affected stands at the young end of this age range may have difficulty growing to merchantable size, so the stands are being either underplanted or cleared and replanted with nonsusceptible species such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.).

Until recently, commercial thinning in older Douglas-fir stands has been a common practice to improve individual tree vigor, accelerate diameter growth, and capture some early return on reforestation investments. Nevertheless, industrial forest landowners now avoid commercial thinning on sites with moderate to severe levels of SNC. However, public land managers must rely more heavily on thinning to achieve silvicultural objectives that involve enhanced stand structural diversity. The largest concentration of state-owned timberland, the 147 000 ha Tillamook State Forest, is on the northwestern Oregon coast, where SNC is especially problematic. One typical example is the large area of state forest

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in north coastal Oregon, most of which resulted from a massive reforestation effort following four major fires over almost 144 000 ha from 1933 to 1951 (Fick and Martin 1993). Over 70 000 ha is covered by 26- to 55-year-old Douglas-fir. Thinning is a key component of a structure-based management plan designed to maintain a healthy forest and future silvicultural options (Oregon Dept. of Forestry 2001). Although the management plan calls for 40%–60% of the land base to be covered by layered, or two-storied, stands (Oregon Department of Forestry 2001), SNC may be a serious obstacle if stands do not respond or even decline after thinning. In younger stands, previous work has suggested that thinned Douglas-fir stands with severe SNC do not generally experience a worsening of symptoms, an increase in mortality, or an acceleration of growth loss. Thinned stands in New Zealand showed infection rates similar to those in unthinned controls and had as much foliage 5 years after thinning (Hood and Sandberg 1979). Another New Zealand study was inconclusive about the effect of different levels of thinning on basal area growth in diseased stands (Manley 1985, unpublished data). More recent work indicates that precommercial thinning of SNC-affected Douglas-fir, even under severe SNC, does not intensify disease development in younger stands (Kanaskie and Maguire 2004). The thinning response of older stands (30–60 years old) with varying degrees of SNC damage is largely unknown. However, many private and public foresters currently must make complex stand management decisions about the feasibility of thinning in the presence of SNC, but the evidence for both positive and negative thinning response is limited.

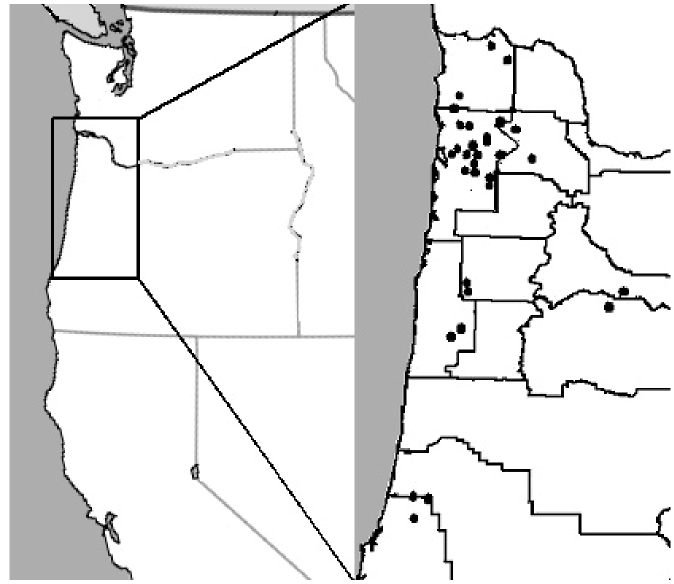
This study addresses the retrospective phase of a project designed to assess the effect of commercial thinning on development of disease symptoms and growth of trees and stands. The retrospective study targeted 30- to 60-year-old Douglas-fir stands thinned between 5 and 10 years ago and showing a varying severity of current SNC. The objective was to test the following hypotheses: (1) volume and basal area growth both before and after thinning were lower where current SNC is severe; (2) residual trees in all stands, regardless of current SNC severity, respond positively to thinning; and (3) response to thinning declined with increasing level of current SNC severity.

Materials and methods

The study sites were located on state land in the Oregon Coast Range and west side of the Oregon Cascades Mountains. The Cascades sites were used to ensure representation of very light SNC severity (Freeman 2002). Latitudes ranged from 43.5°N to 46.16°N, longitudes from 124.06°W to 122.31°W, and elevation from 30 to 800 m a.s.l. (Fig. 1). Over the last 40 years, the mean January minimum for this region was 0 °C and the mean July maximum was 25 °C. Total annual precipitation averaged 150–300 cm, with approximately 70% of the total falling from October to March (http://www.ocs.oregonstate.edu/index.html).

Forty-five fixed-area plots were established during the winters of 2001 (24 plots) and 2002 (21 plots) (Table 1). These plots were measured during the dormant season, and annual basal area growth was reconstructed for varying periods before and after the last thinning. Plot locations were distributed across a range of disease severity classes and residual densities and included different aspects and slopes. Target stands were 30–60 years of age, contained at least 75% by basal area of Douglas-fir, and had undergone commercial thinning 4–10 years ago.

Fig. 1. Plot locations in Oregon.



In a representative part of each stand, a square 0.2-ha plot (0.5 acre) was established. On each plot, all trees >5 cm were tagged and measured for DBH (nearest 0.1 cm), and a subsample of 40 Douglas-fir were measured for total height and height to lowest live branch (nearest 0.01 m). This subsample included the 10 largest Douglas-fir by DBH and the 4 smallest by DBH, with the remaining 26 distributed evenly across the diameter range of the plot. All Douglas-fir were cored for sapwood width, and annual radial growth was measured over a period twice as long as the time since the last thinning. Sapwood area at crown base was estimated using a previously constructed sapwood taper equation for Douglas-fir (Maguire and Batista 1996). Ages were obtained for the 10 largest Douglas-fir, and foliage retention on the same 10 trees provided an estimate of SNC infection severity. Foliage retention was estimated by averaging retention on three to five secondary branches in the upper part of the middle crown third.

Analysis

Four different variables were computed to assess growth response to thinning at the plot level: (1) periodic annual basal area increment; (2) periodic annual volume increment; (3) ratio of postthinning to prethinning basal area growth; and (4) the annual basal area growth over the first 5 years since thinning. The ratio of postthinning to prethinning basal area growth was based on the residual trees only, since growth of the cut trees prior to thinning was unknown. Twenty plots were thinned a sufficiently long time ago that two 3-year growth periods were available prior to thinning. To gain perspective on expected growth trends, ratios of basal area growth for the two successive growth periods prior to thinning were also calculated for these 20 plots (residual trees only).

Past height growth of the 10 Douglas-fir (site) trees with the largest DBH was estimated from site index equations

Table 1. Average attributes for plots in retrospective thinning study.

Attribute	Distance from coast (km)	Site index (m/50 years)	RD* (at thinning) ($m^2 \cdot ha^{-1} \cdot cm^{-0.5}$)	QMD-DF (at thinning) (cm)	Foliage retention (years)	CL:SA (cm/cm^2)	Douglas-fir BA (at thinning) (m^2/ha)	BA for other species (m^2/ha)	Age (years)	Years since thinning
Mean	36.6	38.9	4.46	37.7	2.7	8.95	26.65	0.69	42.3	5.98
SD	29.4	4.5	1.07	7.1	0.7	2.66	6.81	1.36	10.1	1.51
Max.	131	47.2	6.97	56.1	4.38	18.05	44.45	7.07	69.3	10
Min.	8	27.7	2.29	27.6	1.63	4.56	14.29	0	28.4	4

Note: BA, basal area; CL:SA, crown length / sapwood area ratio.
*RD (metric), relative density (from Curtis 1982).

Table 2. Parameter estimates for eqs. 1 and 2 describing periodic annual basal area increment (PBAI) since thinning (model [1]) and periodic annual volume increment (VOLPAI) since thinning.

	PBAI [1]		VOLPAI [2]	
Parameter	Estimate	SE	Estimate	SE
a_0	–1.79787	0.96990	2.10631	0.60107
a_1	0.29012	0.10602	0.15364	0.06637
a_2	–0.60114	0.17988	–0.33803	0.10924
a_3	1.30168	0.22820	0.03548	0.00633
a_4	0.58734	0.10986	0.73945	0.06852
a_5	–1.39642	0.22976	–0.39435	0.21907
a_6	1.19009	0.57224	–0.00571	0.00281

Note: SE, standard error.

(Bruce 1981) and applied to all trees. Letting t be the time since thinning, the estimated heights in years $2001 - t$ and $2001 - 2t$ were combined with the tree basal area backdated to $2001 - t$ and $2001 - 2t$ to calculate an average volume to basal area ratio (VBAR) for each plot in $2001 - 2t$, $2001 - t$, and 2001. Plot volumes were calculated by multiplying each VBAR by plot basal area.

To isolate the "effect" of current SNC severity on growth response to thinning, the response variables mentioned previously were regressed on foliage retention and crown sparseness (CL:SA, the ratio of live crown length / crown base sapwood area; Maguire and Kanaskie 2002), as well as on other covariates that typically influence stand growth. The latter variables included Douglas-fir basal area, basal area of other species, site index, relative density, average crown ratio, average crown length, stand age, and indicator variables representing location and site effects.

Accurate interpretation of the results of annual basal area growth required a baseline for comparison. This baseline was estimated from the SMC variant of ORGANON for a Douglas-fir stand with a similar site index (38 m at 50 years) and management history to the average stand in this data set (Hann et al. 1997). Starting at age 20 with a precommercially thinned stand (500 trees/ha), three management scenarios were simulated: (1) grow to 70 years breast-height age with no treatment, (2) thin at age 35 (from a relative density of 8.50 to 5.04) and grow to age 70, and (3) same as treatment (2), but thin a second time at age 60 (from a relative density of 8.35 to 5.04) and grow to age 70. Periodic growth ratios of each treatment were then calculated at 5-year intervals, with the total basal area growth of the period immediately following thinning compared only with basal area growth of the same trees prior to thinning.

Determination of a thinning response required looking at trends in annual basal area growth in the 5 years following thinning. Because the 1-year measurement intervals created a problem with serial correlation, a repeated measures statement was included in SAS PROC MIXED (SAS Institute Inc. 1999) to adjust parameter values and standard error estimates accordingly.

Results

Periodic annual basal area increment

Plot attributes varied considerably (Table 1), underscoring the need to account for covariates other than those representing SNC severity. Only 3 of the 45 plots contained more than 10% of their basal area in species other than Douglas-fir, and 22 of the plots averaged 97.7% Douglas-fir. Plot basal area growth since thinning was significantly related to current SNC severity and other covariates reflecting site quality and stand density. Approximately 71% of the variation in the logarithm of periodic annual basal area increment was explained by the following model (mean square error (MSE) = 0.025):

$$[1] \quad \ln(\mathrm{PBAI}) = a_0 + a_1\ln(\mathrm{FOLRET}) + a_2\ln(\mathrm{CL{:}SA}) + a_3\ln(\mathrm{SI}) + a_4\ln(\mathrm{RD}) + a_5\ln(\mathrm{CL}) + a_6(\mathrm{CR})$$

where

PBAI is predicted periodic annual basal area increment of the plot since thinning ($m^2 \cdot ha^{-1} \cdot year^{-1}$);
FOLRET is current average foliage retention for the plot (years);
CL:SA is current average crown length / sapwood area ratio for the plot (cm/cm^2);
SI is 50-year site index (m) (Bruce 1981);
RD is plot relative density immediately after thinning ($m^2 \cdot ha^{-1} \cdot cm^{-0.5}$) (Curtis 1982);
CL is average current crown length (m); and
CR is average current crown ratio (expressed as a proportion).

Parameter estimates (Table 2) indicated that stand-level PBAI increased with increasing FOLRET, SI, RD, and CR and decreased with increasing CL:SA and CL. Longer crowns at a given RD and CR indicated greater average tree size

Fig. 2. Periodic annual basal area increment implied by model [1], assuming approximately mean values for site index (38.0 m, 50 years), crown length (16.68 m), and relative density (5.04). CL:SA, crown length / sapwood area ratio.

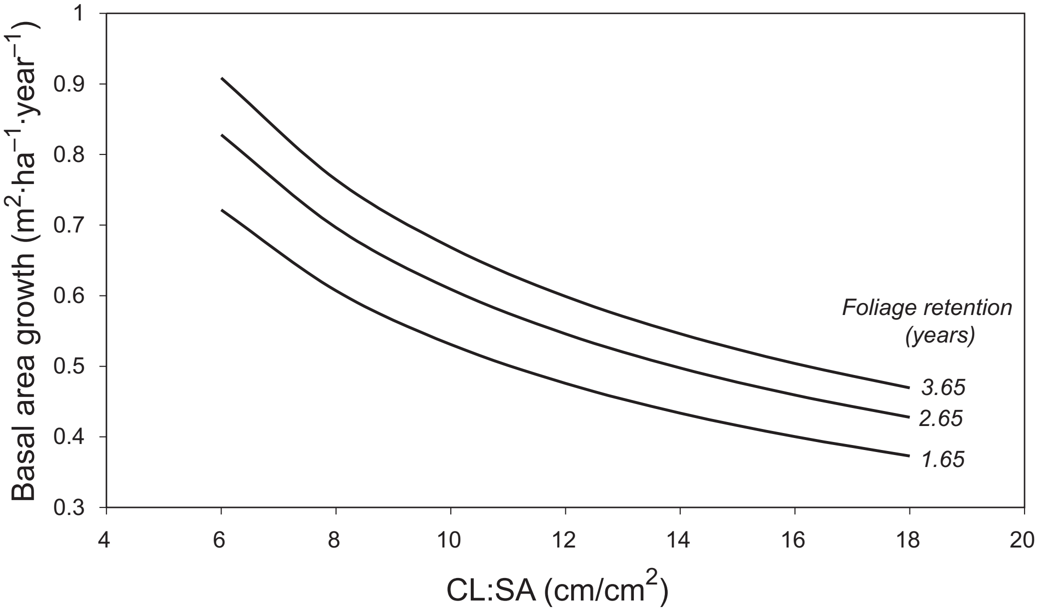
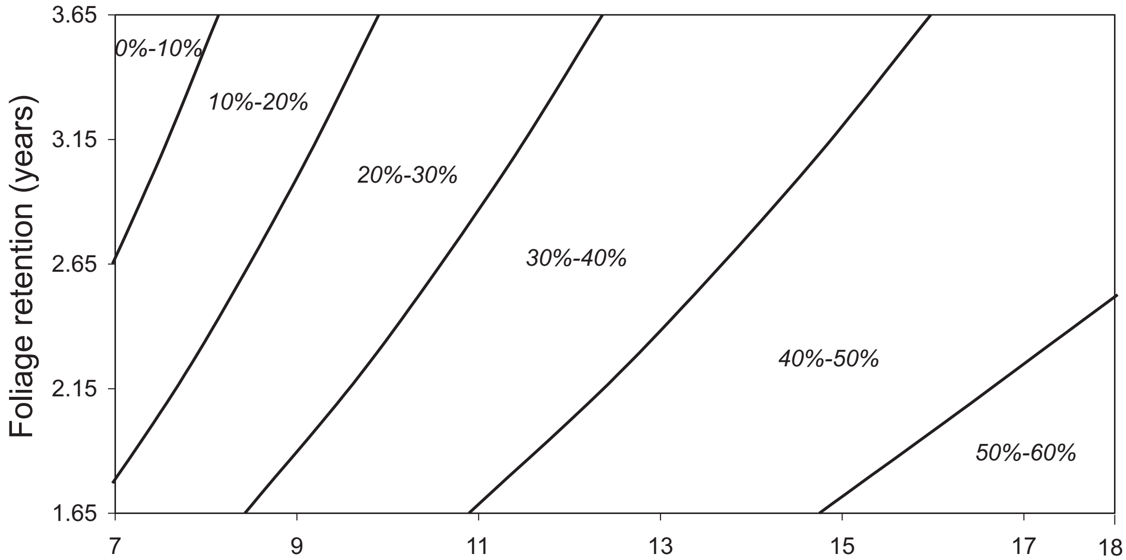


Fig. 3. Basal area growth loss implied by model [1], assuming a maximum foliage retention of 3.78 years, a minimum crown length / sapwood area (CL:SA) ratio of 6.4 cm/cm^2, and approximately mean values for site index (38.0 m, 50 years), crown length (16.68 m), and relative density (5.04).



(and probably age), lower thinning intensity, and (or) fewer residual trees per unit area.

Both FOLRET and CL:SA were effective indices of disease severity and were strongly correlated with stand growth (Fig. 2). The positive effect of FOLRET and negative effect of CL:SA on PBAI were consistent with previously documented declines in growth with increasing SNC severity (Maguire and Kanaskie 2002; Maguire et al. 2002).

If the healthiest stand was assumed to have the highest value of FOLRET and the lowest value of CL:SA (approximately 3.8 years for FOLRET and 6.4 cm/cm^2 for CL:SA), basal area growth losses associated with severe SNC were as high as 55% (minimum retention = 1.63 years and maximum CL:SA = 18.0 cm/cm^2) (Fig. 3).

Periodic annual volume increment

Plot volume growth after thinning was also significantly related to current SNC severity as well as other covariates representing site quality, stand density, and tree age. Approximately 88% of the variation in the logarithm of periodic annual volume increment (VOLPAI) was explained by the following model (MSE = 0.00978):

Fig. 4. Periodic annual volume increment implied by model [2], assuming approximately mean values for site index (38.0 m, 50 years), crown length (16.68 m), and relative density (5.04). CL:SA, crown length / sapwood area ratio.

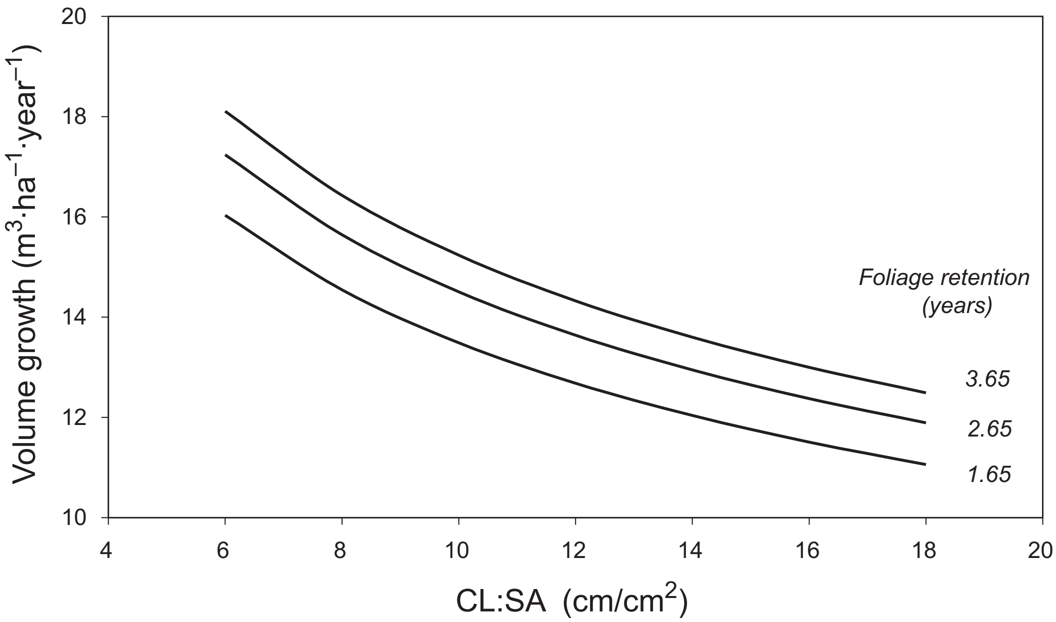


Fig. 5. Volume growth loss implied by model [2], assuming a maximum foliage retention of 3.78 years, a maximum crown length / sapwood area (CL:SA) ratio of 6.4 cm/cm^2, and mean values for site index (38.0 m, 50 years), crown length (16.68 m), and relative density (5.04).

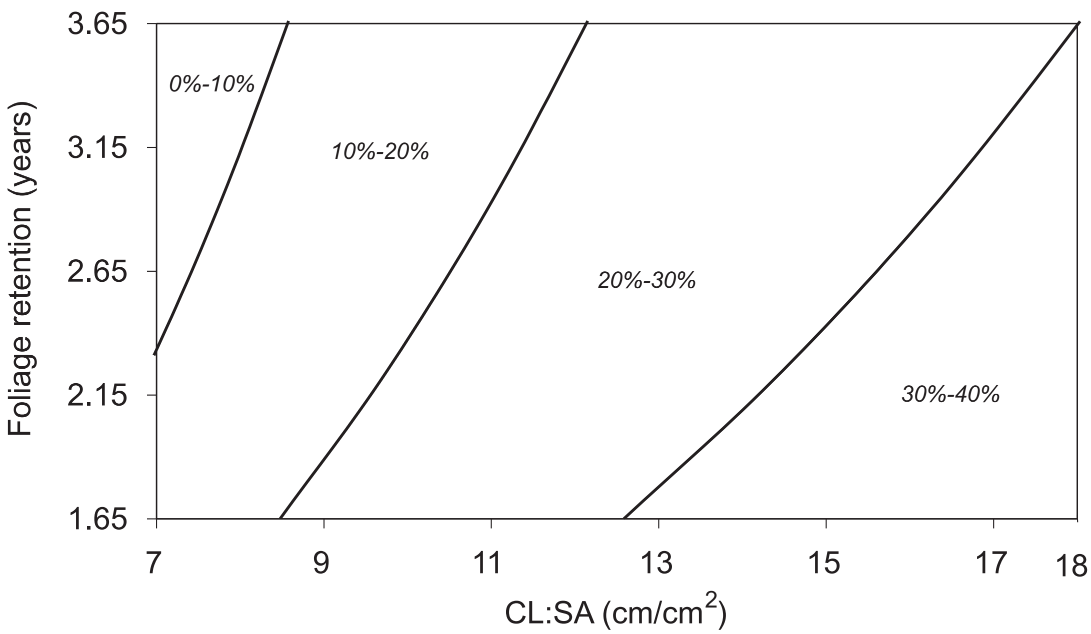


Table 3. Parameter estimates for model describing the ratio of basal area growth after thinning to the basal area growth before thinning (model [4]).

Parameter	Estimate	SE
c_0	0.84969	0.51392
c_1	0.22002	0.09661
c_2	–0.09764	0.02480
c_3	0.01496	0.00563
c_4	–0.38975	0.16966

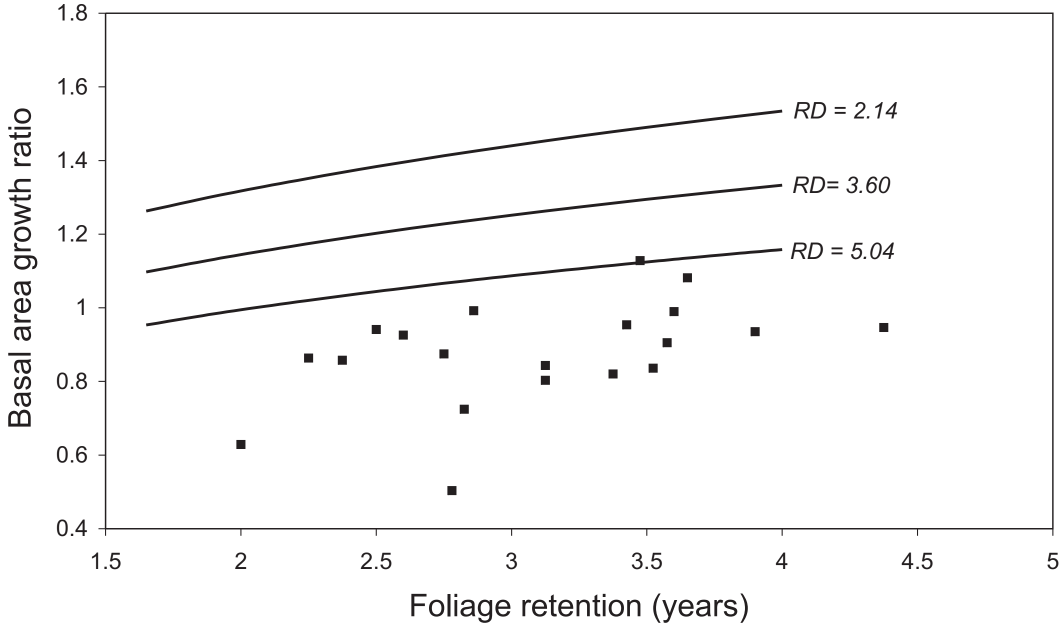
Note: SE, standard error.

$$[2] \quad \ln(\text{VOLPAI}) = a_0 + b_1\ln(\text{FOLRET}) + a_2\ln(\text{CL:SA}) + a_3\text{SI} + a_4\ln(\text{RD}) + a_5\ln(\text{CL}) + a_6\ln(\text{AGE})$$

where VOLPAI is predicted periodic annual volume increment of the plot since thinning ($m^3 \cdot ha^{-1} \cdot year^{-1}$); AGE is average current breast-height age for the plot (years); and FOLRET, CL:SA, SI, RD, and CL are as defined previously.

Parameter estimates (Table 2) indicated that stand-level VOLPAI increased with increasing FOLRET, SI, and RD and decreased with increasing CL:SA, CL, and AGE.

Fig. 6. Postthinning / prethinning basal area growth ratio as a function of foliage retention and stand density (RD). Trends are estimated from model [4], assuming site index 38.0 m at 50 years and average crown length of 16.68 m. Solid squares represent the ratio of basal area growth for the period 3 years before thinning (t – 3 to t) to the basal area growth 3 years prior to that period (t – 6 to t – 3).



Volume growth varied dramatically across the range in FOLRET and CL:SA (Fig. 4). Average volume growth for stands having the lowest levels of FOLRET and highest levels of CL:SA only reached 64% of the potential growth (Fig. 5).

Ratio of postthinning to prethinning basal area growth for residual trees

The ratio of basal area growth after thinning to the basal area growth of the residual trees before thinning was significantly related to SNC severity, in addition to site quality and stand density. Approximately 41% of the variation in postthinning / prethinning basal area growth was explained by the following model (MSE = 0.026):

$$[3] \quad \mathrm{BAGRAT} = d_0 + d_1\ln(\mathrm{FOLRET}) + d_2\mathrm{RD} + d_3\mathrm{SI} + d_4\ln(\mathrm{CL})$$

where BAGRAT is postthinning / prethinning basal area growth ratio and FOLRET, RD, SI, and CL are as defined previously.

Parameter estimates (Table 3) indicate that the postthinning / prethinning basal area growth ratio increased with increasing FOLRET and SI, but decreased with increasing RD and CL in stands thinned between 4 and 10 years ago. At an RD of 5.04, postthinning basal area growth equaled or exceeded prethinning growth (BAGRAT) of the same trees at FOLRET of 2.1 years and above; below 2.1 years, postthinning basal area growth was less than prethinning growth and decreased at an increasing rate as FOLRET declined. At low FOLRET levels, heavier thinning or lower residual stand density evoked a greater basal area growth in the postthinning period relative to prethinning growth.

The latest season of growth included in the prethinning growth ratio was 1997, and the average current FOLRET of the 20 stands used in this comparison was 3.1 years, suggesting limited influence of SNC. The average basal area growth ratio for the two successive 3-year growth periods prior to thinning was 0.92 and ranged from 0.50 to 1.13 (Fig. 6). As with the postthinning to pre-thinning ratio, the pre-thinning growth ratio pertained only to the component of the stand represented by the residual trees. Given that the model implied a ratio of 0.95 at an RD of 5.04 and a FOLRET of 1.63 years, the growth of this stand component after thinning appears little better than its growth in competition with other trees in an unthinned stand. The growth ratio estimated by ORGANON increased substantially only in the single period following thinning (1.27 at 35 years and 1.26 at 60 years). Without thinning, the growth ratio averaged 0.85–0.90 (Fig. 7), indicating that even a growth ratio of 0.95 likely represented a positive response to thinning.

Annual basal area growth

The annual postthinning basal area growth (ABAGR) for each of the first 5 years after thinning was significantly related to Douglas-fir basal area, FOLRET, CL:SA, and AGE.

$$[4] \quad \mathrm{ABAGR} = d_0 + d_1\times\mathrm{DFBA} + d_2\times\mathrm{FOLRET} + d_3\times\mathrm{CL{:}SA} + d_4\times\mathrm{AGE} + d_5\times\mathrm{Y1} + d_6\times\mathrm{Y2} + d_7\times\mathrm{Y3} + d_8\times\mathrm{Y4}$$

where ABAGR is annual basal area growth in year x;
DFBA is Douglas-fir basal area (m^2/ha);
Y1 = 1 if first year after thinning, 0 otherwise;
Y2 = 1 if second year after thinning, 0 otherwise;
Y3 = 1 if third year after thinning, 0 otherwise;
Y4 = 1 if fourth year after thinning, 0 otherwise; and
FOLRET, CL:SA, and AGE are as defined previously.

Once serial correlation was adjusted for, parameter estimates (Table 4) indicated that the average response of stands was positive, and, contrary to hypothesis three, did not depend on the level of SNC (Fig. 8).

Fig. 7. postthinning / prethinning basal area growth predicted by the Swiss needle cast variant of ORGANON for pure Douglas-fir stands (site index 38.0 m at 50 years).

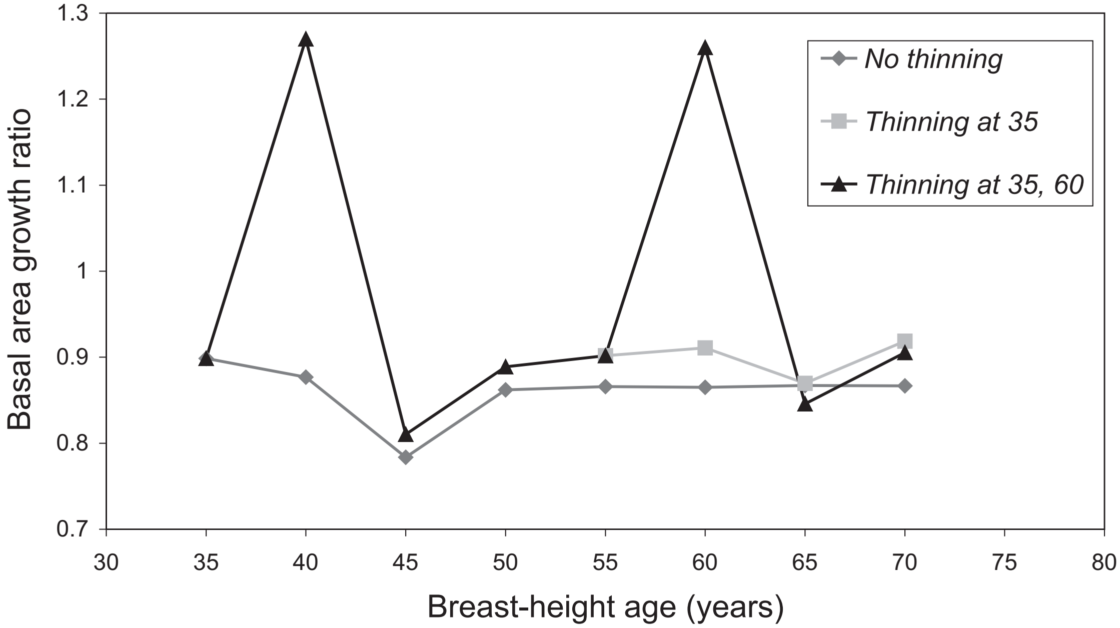


Table 4. Parameter estimates for eqs. 1–4.

Parameter	Estimate	SE
d_0	1.4248	0.5427
d_1	0.6482	0.1185
d_2	0.2553	0.1101
d_3	–0.2581	0.1108
d_4	–0.9746	0.1292
d_5	–0.3421	0.03476
d_6	–0.3030	0.03525
d_7	–0.1493	0.02304
d_8	–0.0792	0.01768

Note: Standard *d* for model describing the per-year annual basal area growth for 5 years following thinning. SE, standard error.

Discussion

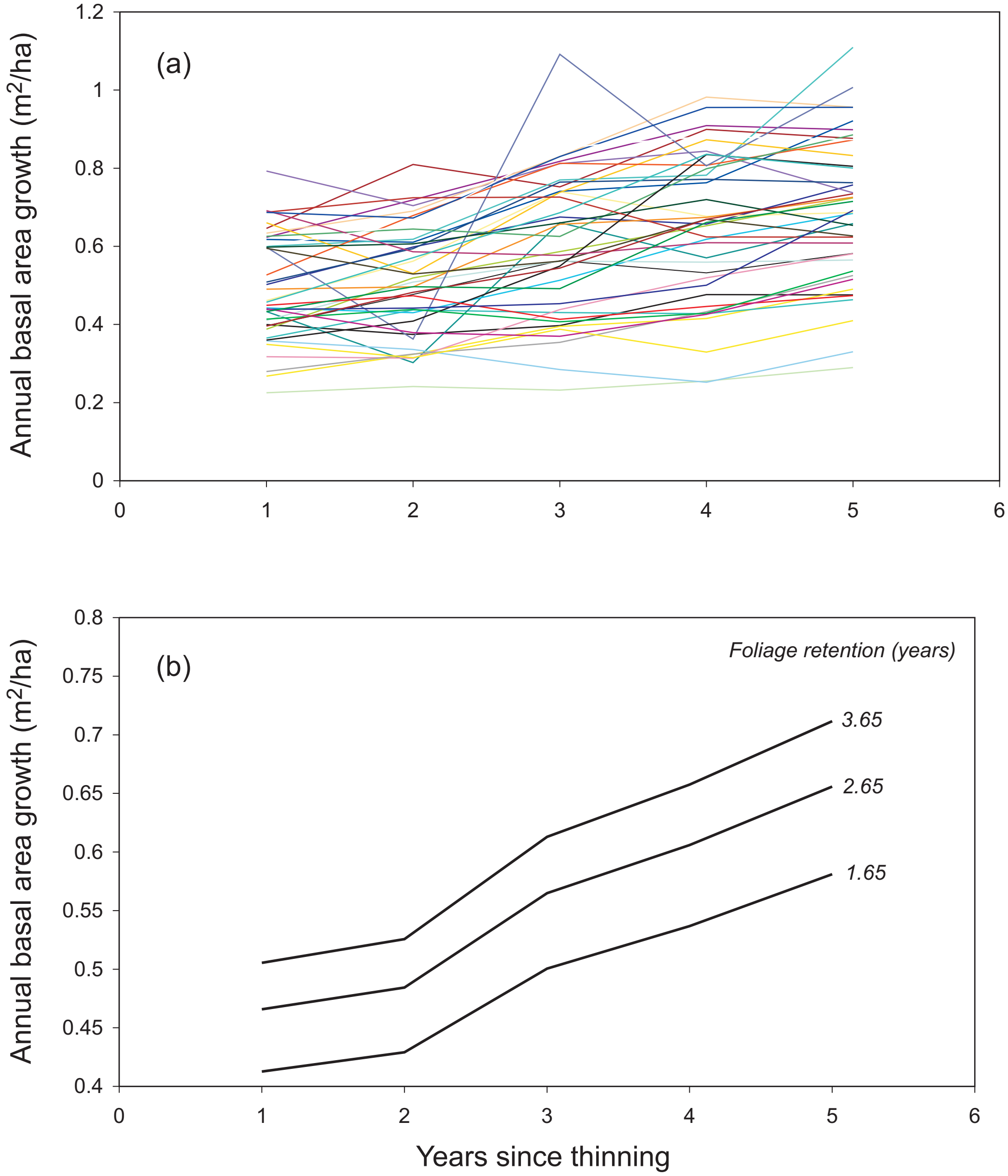
Previous studies in 10- to 30-year-old Douglas-fir plantations in north coastal Oregon suggested that volume growth losses from SNC can reach 50% (Maguire et al. 2002). In this study, volume growth loss under the most severe SNC averaged only 36% (Fig. 5), probably because the lowest foliage retention (FOLRET) was 1.63 years, in contrast to 1.1 years in Maguire et al. (2002). In addition, volume growth losses at the lowest FOLRET levels may be slightly underestimated given the assumptions made in calculating volumes. Reconstructing height growth from SI or height growth equations is problematic for plots that have been experiencing high levels of SNC, because heavily infected trees usually exhibit decreased height growth. Actual height growth of individual trees within these stands would be less than expected based on SI estimated from current height and age, particularly if height growth slowed only recently because of SNC (Maguire et al. 2002). In this case, height growth prior to SNC would suggest a higher SI than after SNC, and SI based on the cumulative height growth over both periods would lead to overestimates of height growth expected under SNC. In addition, because diminished height growth usually appears only in the most heavily infected stands (Maguire et al. 2002), underestimates of volume growth losses would be greater at lower needle retention and high CL:SA.

Postthinning / prethinning growth ratios lend additional insight into stand response to thinning. Because this ratio is not necessarily expected to equal one, the actual growth ratios must be compared with ratios expected under disease-free conditions. In the absence of thinning, this ratio was about 0.85–0.90 in the population studied, reflecting the long slow decline in growth characteristic of most species. However, the growth ratio increased after thinning to levels commensurate with the regional averages represented in current growth models (Fig. 6 compared with Fig. 7). Even Douglas-fir trees severely infected with SNC showed some response to thinning, on average, because their growth ratio tended to be greater than if no thinning was performed.

The implied response indicated by postthinning / prethinning growth ratio is more directly shown by basal area growth over successive years after thinning. Although basal area growth after thinning is diminished by the presence of SNC, both FOLRET × YEAR and CL:SA × YEAR interactions were insignificant, indicating that, on average, infected stands respond to thinning (Fig. 8). This suggests that growth can be accelerated or maintained by thinning and that thinning can remain a viable part of the management strategies for achieving structural diversity. However, the period of time required would be longer and residual stocking should probably be higher to maintain site occupancy. Initial concerns over apparent declines in growth and vigor after thinning in the presence of SNC were not substantiated by this study.

This retrospective study does have some limitations related to the assumption that SNC severity has been stable in

Fig. 8. Annual basal area growth of Douglas-fir for 5 years following thinning: (*a*) average growth trend for each plot and (*b*) growth implied by model [4], assuming mean values for basal area (26 m^2/ha), crown length / sapwood area ratio (8.76 cm/cm^2), and age (42.2 years). Averages were based on 41 plots with at least 5 years of postthinning growth.



any given stand for approximately 20 years. Results from paired thinned and unthinned permanent plots show that 2 years after thinning, FOLRET is only minimally affected by thinning. This effect, while negative at the lowest FOLRET, would amount to a loss of less than 0.1 years of foliage on the most heavily infected plots of this study (Mainwaring et al. 2004). Although 2-year results cannot account for changes in FOLRET attributable to larger scale variation in disease severity over the time interval covered by this study, they do indicate that these changes are generally not attributable to thinning.

This study considered only current SNC levels in estimating past growth responses to thinning, but the results provided some insight into the advantages and risks of conventional thinning in stands where SNC severity is high. Even at low FOLRET, basal area growth of individual trees was, on average, improved by thinning. However, if the goal is to maintain a certain growth rate on individual trees, the stand would have to be thinned to a lower RD under heavy SNC. For example, a stand with a FOLRET of 1.94 years and an RD of 3.58 would have a basal area growth ratio equal to a “healthy” stand (having a FOLRET of 3.65 years) thinned to an RD of 5.04 (based on eq. 3). Conversely, to maintain a minimal level of stand-level basal area growth, residual density should be higher where SNC is more severe (Fig. 7). In essence, a higher RD or basal area is required to retain the same level of site occupancy because of the low leaf area density of severely infected stands (Weiskittel 2003).

Conclusion

On forestland managed predominantly for timber production, the absolute response to thinning in heavily infected stands may be unacceptably low. However, on an ownership managed with the objective of producing both timber and a diversity of stand structures for wildlife and aesthetics (Oliver 1992; Oregon Department of Forestry 2001), holding stands even when their productivity is below the standards normally deemed acceptable can be a reasonable forest-level strategy. Thinning maintained and promoted growth under heavy SNC, so thinning remains a viable option for achieving a diversity of stand structures even where SNC is considered a problem. Thinning did not appear to heighten the growth decline.

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References

Boyce, J.S. 1940. A needle-cast of Douglas-fir associated with *Adelopus gaumanni*. Phytopathology, **30**: 649–659.

Bruce, D. 1981. Consistent height-growth and growth-rate estimates for remeasured plots. For Sci. **27**: 711–725.

Curtis, R.O. 1982. A simple index of stand density for Douglas-fir. For. Sci. **28**: 92–94.

Freeman, F. 2002. Swiss needle cast monitoring in the Oregon Cascades. *In* 2002 Annual report. Swiss Needle Cast Cooperative, College of Forestry, Oregon State University, Corvallis, Ore. pp. 11–14.

Fick, L., and Martin, G. 1993. The Tillamook Burn: rehabilitation and reforestation. Oregon Department of Forestry, Forest Grove, Ore.

Hann, D.W., Hester, A.S., and Olsen, C.L. 1997. ORGANON user's manual: edition 6.0. Department of Forest Resources, Oregon State University, Corvallis, Ore.

Hansen, E.M., Stone, J.K., Capitano, B.R., Rosso, P., Sutton, W., Winton, L., Kanaskie, A., and McWilliams, M. 2000. Incidence and impact of Swiss needle cast in forest plantations of Douglas-fir in coastal Oregon. Plant. Dis. **84**: 773–778.

Hood, I.A., and Sandberg, C.J. 1979. Changes within tree crowns following thinning of young Douglas-fir infected by Phaeocryptopus gaeumannii. N.Z. J. For. Sci. **9**: 177–184.

Kanaskie, A., and Maguire, D. 2004. Trends in Swiss needle cast damage in thinned and unthinned Douglas-fir plantations with varying intensity of Swiss needle cast in the Coast Range of Oregon. *In* 2004 Annual report. Swiss Needle Cast Cooperative, College of Forestry, Oregon State University, Corvallis, Ore. pp. 17–23.

Kanaskie, A., McWilliams, M., Sprengel, K., and Overhulser, D. 2004. Swiss needle cast aerial surveys, 1996–2004. *In* 2004 Annual report. Swiss Needle Cast Cooperative, College of Forestry, Oregon State University, Corvallis, Ore. pp. 7–11.

Maguire, D.A., and Batista, J.L.F. 1996. Sapwood taper models and implied sapwood volume and foliage profiles for coastal Douglas-fir. Can. J. For. Res. **26**: 849–863.

Maguire, D.A., and Kanaskie, A. 2002. The ratio of live crown length to sapwood area as a measure of crown sparseness. For. Sci. **48**: 93–100.

Maguire, D.A., Kanaskie, A., Voelker, W., Johnson, R., and Johnson, G. 2002. Growth of young Douglas-fir plantations across a gradient in Swiss needle cast severity. West. J. Appl. For. **17**: 86–95.

Mainwaring, D.B., Maguire, D.A., Kanaskie, A., and Brandt, J. 2004. Interactive effects of Swiss needle cast and commercial thinning on Douglas-fir growth and development in north coastal Oregon — results from the first 15 permanent plots. *In* 2004 Annual report. Swiss Needle Cast Cooperative, College of Forestry, Oregon State University, Corvallis, Ore. pp. 80–90.

Manley, B. 1985. Growth loss of Douglas-fir associated with *Phaeocryptopus* in Kaingaroa Forest. *In* Management Policy for Douglas-fir, Workshop, Nelson, 26–28 March 1985. New Zealand Forest Service (unpublished). Available from New Zealand Forest Research Institute Ltd., Private Bag 3020, Rotorua, New Zealand.

Oliver, C.D. 1992. A landscape approach: achieving biodiversity and economic productivity. J. For. **90**: 20–25.

Oregon Department of Forestry. 2001. Northwestern Oregon State forests management plan: final plan. Jan. 2001. Oregon Department of Forestry, Salem, Ore.

SAS Institute Inc. 1999. SAS/STAT user's guide [computer manual]. SAS Institute Inc., Cary, N.C.

Weiskittel, A. 2003. Alterations in Douglas-fir crown structure, morphology, and dynamics imposed by the Swiss needle cast disease in the Oregon Coast Range. M.S. thesis, Oregon State University, Corvallis, Ore.