Universidad de Valladolid
Campus de Palencia

ESCUELA TÉCNICA SUPERIOR

DE INGENIERÍAS AGRARIAS

Máster
Ingeniería de Montes

The relative productivity and stand structure of Douglas-fir stands with varying levels of red alder retention near Waldport, Oregon (USA)

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Septiembre de 2015

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0. RESUMEN

La zona del Noroeste del Pacífico de los Estados Unidos es una zona dominada por bosques de *Pseudotsuga menziesii* y *Alnus rubra*. Tradicionalmente este tipo de bosques han tenido como objetivo principal la producción de madera y otros materiales para la industria.

Los bosques mixtos de *Pseudotsuga menziesii* y *Alnus rubra* presenta numerosas opciones de manejo, dependiendo de los objetivos, sobre todo teniendo en cuenta la producción de madera junto con el mantenimiento de otros servicios que nos da el monte, como la producción de productos no maderables y la mayor resistencia que ofrece este tipo de masas al ataque de plagas y enfermedades. Últimamente la madera de Alnus rubra ha incrementado su valor y ha empezado a competir con la madera de *Pseudotsuga menziesii* en aquellas sitios donde *Alnus rubra* crece igual de bien o mejor que *Pseudotsuga menziesii*.

Investigaciones previas han estudiado las ventajas y desventajas que puede tener una masa mixta frente a una masa pura, y los resultados hasta ahora obtenidos nos indican que las plantaciones mixtas tienen un mayor rendimiento y producción que las plantaciones puras.

Muchas de estas zonas del Noroeste del Pacífico tienen una limitación de nitrógeno en el suelo lo que nos presenta varias opciones a la hora del manejo. La primera opción es mantener la especie *Alnus rubra* para favorecer la aportación de forma natural de nitrógeno al suelo, y analizar cuánto es el beneficio en los rendimientos totales de producción de madera final de *Pseudotsuga menziesii*. En este caso el número de pies por hectárea a mantener deberá ser determinado en función de la zona en cuestión.

La segunda opción es quitar todos los pies de *Alnus rubra* y fertilizar con nitrógeno, sobre todo en aquellas situaciones donde la producción de madera es un objetivo prioritario.

Partiendo de esta situación inicial, este estudio trata de obtener resultados comparando distintas opciones de manejo de masas mixtas de *Pseudotsuga menziesii* y *Alnus rubra*, buscando el mayor rendimiento de *Pseudotsuga menziesii*.

La zona de estudio se localiza en Waldport Ranger District of the Siuslaw National Forest, en la zona costera, en el oeste del estado de Oregon (EEUU). Es una plantación que a los 9 años, en el invierno de 1979-1980 fue sometida a una clara en la que se redujo el número de pies de *Pseudotsuga menziesii* a 300 pies/acre en todas las parcelas, quitando toda la regeneración natural del resto de especies presentes en la zona. Junto con la presencia en todas las parcelas de 300 pies/acre de *Pseudotsuga menziesii*, se llevaron a cabo distintos tratamiento.

El diseño experimental consiste en comparar en crecimiento en volumen de las especies *Pseudotsuga menziesii y Alnus rubra*, en parcelas con una densidad constante de *Pseudotsuga*

menziesii con distintas densidades de *Alnus rubra*,y con parcelas fertilizadas sin presencia de *Alnus rubra*.

Una vez establecido el diseño experimental se va a comparar los distintos resultados para ver si hay alguna diferencia en cuanto a producción de volumen total en las siguientes situaciones:

-Parcelas con distintas densidades de *Alnus rubra* 0, 20, 40, 80 pies/acre, con una densidad constante de 300 pies/acre de *Pseudotsuga menziesii*.

-Parcelas con 300 pies/acre de *Pseudotsuga menziesii* fertilizadas con nitrógeno y sin fertilizar.

-Parcelas que han sufrido una clara inicial con densidades de 300 pies/acre de *Pseudotsuga menziesii*.

-Parcelas sin ningún tipo de tratamiento.

La conclusión general que podemos obtener a partir de los resultados obtenidos es que tras 25 años de estudio el mayor volumen se encuentra en aquellas parcelas que no han recibido ningún tipo de tratamiento. Los pies localizados en estas parcelas fueron menores que en aquellas que si que recibieron algún tipo de tratamiento.

La mayor presencia de *Alnus rubra* supuso un incremento en la densidad total de las parcelas pero esto no supuso un aumento del volumen total, debido a que *Alnus rubra* crece en detrimento de *Pseudotsuga menziesii*.

Los mayores volúmenes de *Pseudotsuga menziesii* fueron obtenidos en aquellas parcelas con presencia exclusiva de esta especie.

Se llega a la conclusión que aquellas parcelas en las que se ha llevado a cabo la eliminación de todas las especies y practicado el cultivo monoespecífico de *Pseudotsuga menziesii* favorece el crecimiento y rendimiento de esta especie con respecto a parcelas mixtas.

El crecimiento de *Pseudotsuga menziesii* se vio afectado de forma negativa por la presencia de *Alnus rubra*, y tampoco se puede indicar que la fertilización haya tenido algún efecto positivo en el crecimiento de dicha especie.

1. INTRODUCTION

The Pacific Northwest hosts many forests dominated by Douglas-fir and/or red alder. Mixed stands of these species offer several challenges and opportunities in regard to competitive interactions and potential facilitation of Douglas-fir by the nitrogen fixing property of red alder. More recently, red alder timber has increased in value, so has also become competitive with Douglas-fir on those sites where red alder grows as well or better than Douglas-fir. Regardless, even in mixtures, the value of red alder wood renders its displacement of Douglas-fir productivity less of an issue than was the case only recently.

Historically, sites that can support Douglas-fir or red alder forests have been used to produce wood or other raw materials for industry. Various societal segments throughout the world have renewed interest in mixed-species forests for numerous reasons: promoting biodiversity at the stand and landscape scales; for their perceived value as more natural forest structures; for their potential production of unique non-timber forest products; and for their ability to lower risk and perhaps resistance to losses from insect and disease attack.

Mixed forests of Douglas-fir and red alder present numerous management options with regard to the specific structure to achieve and maintain, particularly in regard to the relative species composition, size class structure, and spatial distribution of the two species. The most appropriate silvicultural strategy will obviously depend on the stand management objectives, particularly with regard to the tradeoffs between timber production and other ecosystem services.

Past research on mixed-species forest management has explored to some extent the advantages and disadvantages of mixtures compared to pure forests. It is often stated that planting species mixtures will yield greater productivity than pure plantations, as well as other benefits, but the results reported in the literature are not consistent and seem to depend on the species involved, stand age, stand density, whether results were from plantations in a designed experiment or an observational study of naturally regenerated stands, and other conditions.

In their comparison of 12-yr-old mixed and pure plantations of Douglas-fir and western hemlock, Amoroso and Turnblom (2006) found that Douglas-fir had greater height, diameter and volume than western hemlock at all six initial planting densities (244, 478, 747, 1076, 1681, and 2989 trees per ha) . Pure plantations had greater volume than mixed plantations at low densities, but at high densities the productivity was more similar between pure and mixed stands. Other research has demonstrated a similar interaction between species composition and planting density (Garber and Maguire 2004). As was true of the relative growth rate of Douglas-fir and western hemlock (Amoroso and Turnblom 2006), de Montigny and Nigh (2007) reported that Douglas-fir had a faster early growth than western redcedar as the percentage of

Douglas-fir increases in the stand. However, there was not a significant difference in average growth of a given species whether it was grown in a mixed or pure stand, and no interactions with stand density were observed. The lack of significant differences between treatments was attributed to the relative young age of the 14-yr-old plantations (de Montigny and Nigh 2007).

In a comparison of monocultures to mixed plantations of Douglas-fir and western white pine, and to mixtures of Douglas-fir and western hemlock, Douglas-fir height/diameter ratios were significantly less in mixed 20-yr-old stands, but this ratio was larger in the case of Douglas-fir growing with western hemlock (Erickson and others 2009). However, the relative amount of Douglas-fir versus western white pine had no effect growth on yield in this study.

Garber and Maguire (2004) compared the growth, yield, and structural development of mixed species plots to pure plots in a set of 30-yr-old spacing trials in central Oregon. Interaction effects of species composition and spacing were evident on volume and periodic annual growth, and the nature and statistical significance of this interaction changed with stand age. As is typically observed, standing volume and volume growth decreased with increasing spacing. In mixed plots, the less shade tolerant species exhibited the most rapid juvenile height growth and therefore the greatest plot-level volume growth. Conversely, the more shade tolerant species grew less over the same period of time. However, the difference in volume growth of pure plots decreased over the course of stand development. In short, spacing and species composition had a big impact on total production and stand development. Mixed species plantations had similar productivity to pure stands, at least for different stages of stand development observed up to 30 years.

Conversion of pure stands into mixed-species forests is currently of much interest in Europe. Relative growth and yield of a specific species mix is not the primary concern. Rather mixed stands are believed to reduce risk and increase resistance to biotic and abiotic disturbances and diseases. The value of mixed-species forests must consider many ecosystem benefits that include but are not limited to wood production (Knoke and others 2007).

Nunes and others (2014) compared the productivity of different stands of Douglas-fir and *Castanea sativa Mill.*. The mixed plantations were established with different proportions of these two species to assess how growth and yield varied across a compositional gradient, and to identify an optimal composition with respect to yield. Growth was measured for 28 years and resulted in the conclusion that Douglas-fir achieved greater heights and diameters than *Castanea sativa* in mixed stands. However, total yield was greater in mixtures than in pure stands. During the early years of plantation development, total volume was similar between pure and mixed stands, but later mixed-species stands outproduced pure stands.

The potential productivity of mixed stands of Douglas-fir and red alder have received a lot of attention due to the nitrogen-fixing ability of red alder and the resulting potential increase in nitrogen availability, as well as other related benefits such as the higher quality of leaf litter and implications for decomposition and cycling of nutrients. Due to the commonly observed adverse impact of red alder on overtopped Douglas-fir, a major subject of research has been the effect of relative composition and spacing of the red alder and Douglas-fir on total stand productivity. In short, the question has been whether mixing red alder with Douglas-fir can be done in a way that enhances productivity or at least maintains productivity relative to pure stands of either species.

Shainsky and Radosevich (1992) compared the growth of mixtures and pure plantations of Douglas-fir and red alder with different initial densities. Red alder dominated the mixtures and reduced the light available to understory of Douglas-fir.

Many sites occupied by Douglas-fir or Douglas-fir/red alder mixtures are nitrogen-limited, as evidenced by their response to nitrogen fertilization (Peterson and Hazard 1990). Limitation to productivity due to low availability of nitrogen suggests two options for management. One option would be to maintain red alder to promote its contribution to soil nitrogen and its availability to Douglas-fir. In this case, the optimal amount of red alder to retain must be determined for a given site. Where Douglas-fir timber production is a top priority and where it is assumed limited by nitrogen availability, another option would be to fertilize with nitrogen, and remove red alder where it may detract from Douglas-fir productivity.

Rothe and others (2002) investigated the influence of red alder on soil carbon and nitrogen pools. In mixed plots with Douglas-fir and red alder, the amount of nitrogen increased significantly. In pure plots of Douglas-fir the amount of nitrogen stayed constant.

Douglas-fir plantation management typically involves early control of competing vegetation, pre-commercial thinning, and sometimes later fertilization with about 200 lbs nitrogen per acre. Red alder can present a special problem due to its rapid juvenile growth rate and resulting adverse impacts on Douglas-fir survival and growth. This problem is more common in high-quality, mesic sites where the height growth difference between red alder and Douglas-fir is greater that on lower quality dry sites. Red alder can fix 20-300 lb N/acre annually. If we want to know whether the better option for Douglas-fir production is to fertilize or include some red alder, we need to know the positive and negative effects of this mix. For example, it is important to identify the optimal density of red alder and compare production under optimal fertilizer dosage. In the previous studies described above, negative and positive effects of admixed red alder on stand yield, value, and cost effectiveness have been assessed at a wide range of site qualities, relative to applying fertilizer. In operational Douglas-fir stands the optimal fertilizer dosage ranges between 150 and 300 lb N/acre. In nitrogen limited sites, the optimal red alder density has been estimated at 40 trees per acre, assuming these trees are removed in the first commercial thinning. However, the optimal density of red alder probably depends on site quality (Miller et al. 1999).

Grotta and others (2004) studied a plantation of Douglas-fir and red alder with different proportions of both species. When both species were planted in the same year and when red alder density was low, red alder trees had low crown bases and much stem defect and Douglas-fir grew slowly. When red alder planting was delayed, red alder stem form was more acceptable, but the height to the base of live crown in Douglas-fir decreased as red alder density increased. An increase in the density of Douglas-fir resulted in an increase in the height to the crown base in Douglas-fir, but doubling the density of red alder did not affect Douglas-fir crown height.

In Pacific Northwest, a mixed forest of Douglas-fir and red alder often results from natural red alder regenerations in Douglas-fir plantations. Radosevich and others (2006) compared two plantations of Douglas-fir and red alder, one of them in the Cascades Range and another in the Coast Range. Red alder grew better in the Coast Range, while Douglas-fir grew better in the Cascade Range. Removal of red alder improved Douglas-fir growth in the Cascade Range, but did not improve Douglas-fir growth in the Coastal Range. However, the proportion of each species played an important role in determining their relative growth rates and total stand yield, so decisions about the density of each species in a mixture has important consequences for the yield of each species and for the total stand.

In the winter of 1979-80, a 9-yr-old Douglas-fir plantation on the Siuslaw National Forest was scheduled for pre-commercially thinning to 300 Douglas-fir trees per acre, with the objective of removing the abundant naturally-regenerated red alder, Engelmann spruce, Douglas-fir, and western hemlock (Miller et al. 1999). The opportunity was taken to retain 0, 20, 40, or 80 red alder stems per acre on plots that were thinned to 300 planted Douglas-fir trees per acre to test the relative gains and losses possible from mixing red alder with Douglas-fir. For the purpose of comparison, another set of plots was thinned to 300 Douglas-fir per acre and fertilized with nitrogen. Miller et al. (1999) reported on 17-year responses of growth and mortality to the initial treatments. Two additional measurements have been taken on all the plots, so the objective of this analysis was to test 25-yr responses to differing levels of red alder retention relative to unthinned control plots and relative to plots thinned to 300 Douglas-fir and fertilized with urea.

2. OBJECTIVES

The original objectives of this study were:

1. To test the null hypothesis of no significant differences in either Douglas-fir productivity or total stand productivity among plots in which 0, 20, 40, or 80 red alder had been retained during a pre-commercial thinning to 300 Douglas-fir per acre.
2. To test the null hypothesis of no significant difference in Douglas-fir productivity between fertilized and unfertilized plots that had been pre-commercially thinned to 300 Douglas-fir per acre.
3. To test the null hypothesis of no significant difference in Douglas-fir or total stand productivity between plots that had been pre-commercially thinned to 300 Douglas-fir trees per acre and plots that received no silvicultural interventions since planting.
4. To test the null hypothesis of no significant difference in species composition and stand structure among plots receiving the six different silvicultural treatments.

3. MATERIALS AND METHODS

3.1 LOCATION

The study was located within the Waldport Ranger District of the Siuslaw National Forest in western Oregon (44.4259°N 123.9827°W) (figure 1.1). Study plots were located within typically steep Coast Range topography. Aspects were northwesterly, elevation averaged about 800 ft, and slopes ranged between 10 and 70 percent (Miller et al. 1999).

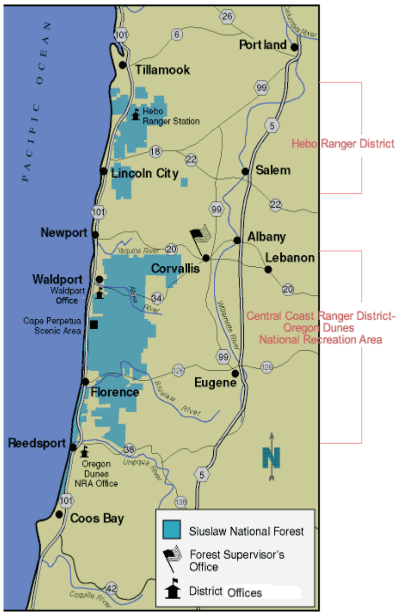

Figure 1.1. Location Siuslaw National Forest, Oregon, USA (U.S. Forest Service).

3.2 EXPERIMENTAL DESIGN

We compared volume growth of Douglas-fir, red alder, and both species together on plots representing varying densities of red alder within a constant Douglas-fir density of 300 trees per acre after pre-commercial thinning. As shown in Table 1, the 0 trees per acre of alder (treatment 1) corresponded to a conventional removal of all red alder by herbicide or cutting. Admixtures of 20, 40, and 80 alder per acre were assumed to cover any financially optimum number of alder to retain in mixed stands (Miller and Murray 1979). Treatment 6 (control treatment with no thinning) corresponded to a management regime in which control of competing red alder and removal of non-crop natural conifers was precluded due to environmental concerns, other stand management objectives, or unaffordable management costs (Miller et al. 1999).

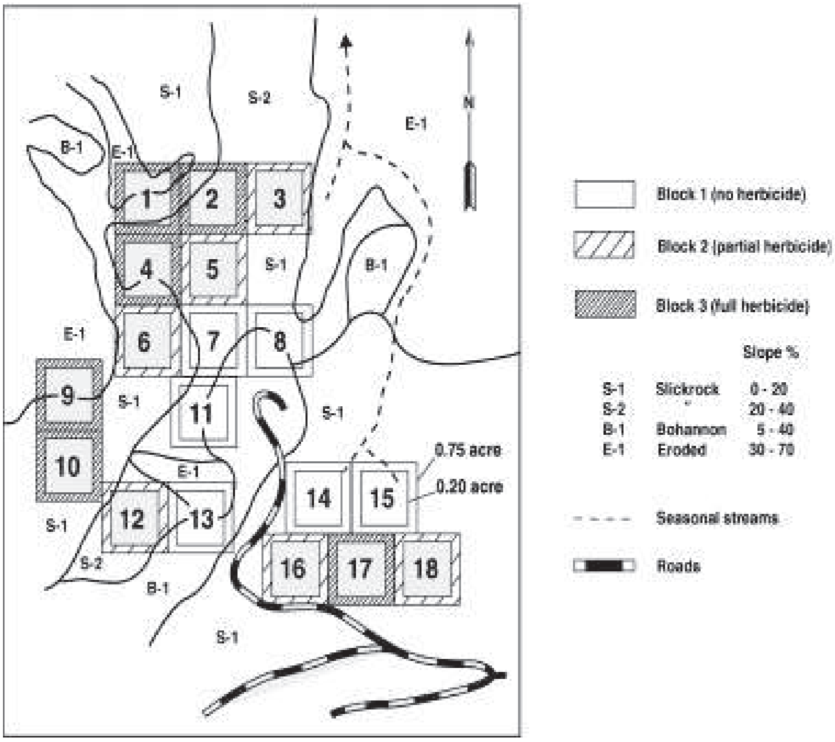

Figure 1.2. Plot locations, size, and blocking based on earlier herbicide application in the experimental area (from Miller et al. 1999).

Table 1: The six silvicultural treatments as defined by residual red alder (0, 20, 40, and 80 stems per acre), fertilization level (0 or 200 lbs N per acre), and pre-commercial thinning vs. no pre-commercial thinning at the Risley Creek Douglas-fir/red alder study.

Treatment	Retained red alder TPA	PCT?	Fertilized?
1	0	Y	N
2	20	Y	N
3	40	Y	N
4	80	Y	N
5	0	Y	Y
6	NA	N	N

The experimental design included three replications of each treatment on square 0.2-ac measurement plots (93.3 x 93.3 ft) with 87.4-ft buffers receiving the same treatment (180.7 x 180.7 ft or 0.75-ac treatment plot). Treatments were allocated randomly within three blocks defined by the relative intensity of herbicide release treatments applied in spring of 1975 (no spray, partial spray, full spray).

3.3 SOILS

Plots of higher site quality were located on Slickrock gravelly clay loam developed from sandstone colluvium of an ancient land flow. Other plots were located on Bohannon gravelly loam (a residual soil also developing on sandstone), on an intergrade between the two series, or on eroded Slickrock (associated with deeply incised draws). Slickrock soils are different from Bohannon by being deeper than 4 ft and having finer textures. Both soils are Andic Haplumbrepts of the heavy, loamy, mixed-acid family. Among the 18 study plots, total N-content in the soil to 39-in depth averaged 11,440 lbs/acre and ranged from 8,000 to 20,700 lbs N/acre (Cromack and others 1999). An additional 100 lbs N/acre were contained in the forest floor developing under the 9-year-old stand (Miller et al. 1999).

3.4 STAND HISTORY

After intense slash burning, this 50-acre clearcut was auger-planted in January 1971 with 2-1 Douglas-fir seedlings grown from locally collected seed. Target spacing was 10 ft by 10 ft. The preceding stand, logged in 1969, was 130-year-old Douglas-fir and hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The preparation of the site before planting consisted of the following activities (Miller et al. 1999):

• August 1969—Preburn spray (2 lb/acre of A.E. Amitrol-T in water; 10 gal of combined solution per acre).

• May 1970—Preburn spray (1 lb/acre of A.E. 2,4-D + 1 lb/acre of 2,4,5-T in water; 10 gal combined solution per acre).

• August 1970—Broadcast burned; over nearly all the unit, fire consumed all forest floor, twigs, and branches.

When the plantation was 4 years old, approximately 30 acres were sprayed with Esteron Brush Killer (1 lb/acre of A.E. 2, 4-D and 1 lb/acre of A.E. 2, 4, 5-T) in water. To avoid damage to a section of the plantation where Douglas-fir buds had already burst, spraying was limited to areas where Douglas-fir was in an earlier physiological state (Miller et al. 1999).

3.5 PLOT INSTALLATION AND TREATMENT

Eighteen plots were installed in the 9-year-old plantation. The 6 treatments were replicated 3 times on square 0.2-ac measurement plots (93.3 x 93.3 ft) with 87.4-ft buffers receiving the same treatment (180.7 x 180.7 ft or 0.75-ac treatment plot). In 15 of these plots, tree density was reduced after the 1979 growing season to about 300 planted Douglas-fir trees per acre. Surplus red alder was controlled with a "hack-and-squirt" herbicide treatment to minimize the probability of sprouting. A fertilization treatment was also replicated three times on a plot that was thinned to only 300 Douglas-fir trees per acre. The fertilizer was applied three growing seasons after plot establishment and thinning at a rate of 200 lbs N per acre as urea. The remaining 3 plots of the 18 were left unthinned and unfertilized (Miller et al. 1999).

3.6 TREE MEASUREMENT AND VOLUME COMPUTATION

In measurement plots, all trees retained were identified by numbered aluminum tags and their diameter at breast height (dbh) was measured to the nearest 0.1 in (Miller et al. 1999). Trees selected for cutting were tallied by 1-in d.b.h. classes. In the following 25 years, dbh and height of retained trees were measured at 3-, 4-, or 5-year intervals.

A subsample of 30 Douglas-fir trees and 8 to 16 red alder trees was measured for height (nearest 0.1 ft) on each plot (Miller et al. 1999). Height-diameter curves were fitted to this subsample of height trees for each combination of plot, measurement year, and species. The model form was as follows:

$ht = 1.37 + g_1*exp(g_2/dbh)$
$g1 = exp(g2/d)$
$g2 = g1*exp(g2/d)*(1/d)$

where ht was total height of the tree in meters, dbh was diameter at breast height in cm, and g_1 and g_2 were parameters estimates specific to a given plot, measurement year, and species. The ht-dbh equations were applied to estimate the height of trees that were measured for only diameter (Table 2), and total stem volume was calculated for each tree from regional volume equations (Table 3) specific to each species, including Douglas-fir (Hann and others 1985), red alder (Brackett 1973) ,western hemlock (Brackett 1973) and sitka spruce (Brackett 1973).

Table 2. Height-diameter equations applied to estimate height of Douglas-fir, red alder, sitka spruce and western hemlock at the Risley Creek Douglas-fir/red alder study (units are meters for h, and centimeter for d).

Species	Height-diameter equation
Douglas-fir	h= (1.37 + (84.92352*(1-exp(-0.010853*d))**0.936797))
Red alder	h= (1.37 + (37.36855*(1-exp(-0.023400*d))**0.761640))
Sitka spruce	h= (1.37 + (65.27757*(1-exp(-0.012361*d))**0.967921))
Western hemlock	h= (1.37 + (60.87614*(1-exp(-0.021948*d))**1.078265))

Table 3. Volume equations applied to estimate standing volume and volume growth of Douglas-fir, red alder, sitka spruce and western hemlock at the Risley Creek Douglas-fir/red alder study (units are cubic meters for volumes, centimeter for dbh, and meter for ht).

Species	Volume equation
Douglas-fir	$V = V_{bbh} + V_{abh}$ $V_{abh} = 0.001168 \cdot [\ (ht\text{-}4.5)/dbh]^{0.265430} \cdot [dbh^2 \cdot (ht\text{-}4.5)]$ $V_{bbh} = (\pi \cdot dibs^2/175616) \cdot [(729 + 81 \cdot (dib/dibs)^{2/3} + 297 \cdot (dib/dibs)^{4/3} + 265 \cdot (dib/dibs)^2]$ $dib = 0.903563 \cdot dbh^{0.989388}$ $dibs = 0.989819 \cdot dbh$
Red alder	$V = 0.04969879 + 0.00247940 \cdot dbh^2 \cdot ht$
Sitka spruce	$V = 355.05775 \cdot dbh^{1.835678} \cdot ht^{1.042599}$
Western hemlock	$V = e^{-6.3054647 + 0.014978752 \cdot dbh} \cdot dbh^{2.0337286} \cdot ht^{1.0849}$

3.7 STATISTICAL ANALYSIS

Individual tree data were summarized for each 3-, 4- and 5-year growth period after thinning: 1980-82, 1983-85, 1986-88, 1989-92, 1993-96, 1996-00, and 2000-05, as well as for the total 25-year period.

Treatment effects on plot-level periodic annual volume increment (VPAI) and periodic annual diameter increment (DPAI), as well as any change in treatment effects over time, were tested by a repeated measures ANOVA. Standing volume in 2005 was tested by one-way ANOVA to test for treatment effects on total 25-yr production of Douglas-fir, and on the production of all species summed.

Differences in species composition among the treatments were assessed graphically by plotting stacked histograms on year of measurement.

4. RESULTS

The initial density of Douglas-fir varied between 970 and 2610 trees per acre at plantation age 9 before the pre-commercial thinning (table 4). The density of red alder varied between 0 and 410 trees per acre, with the lower densities a consequence of herbicide applications 5 years before. Other species also regenerated naturally, so the density of all species summed ranged between 1250 and 5710 trees per acre (Miller et al. 1999).

After thinning, residual Douglas-fir tree density ranged between 293 and 307 per acre, in contrast to the three unthinned plots that averaged 1875 trees per acre (table 5). Quadratic mean dbh (Dq) of residual Douglas-fir in the thinned plots averaged nearly 4.0 inches compared to 1.2 inches for unthinned plots (Miller et al. 1999).

The Dq and mean height of the largest 300 Douglas-fir per ac on the unthinned plots were similar to those on the thinned plots. Unthinned plots averaged 10 times more trees of all species combined, than the thinned plots that retained the most alder (80 alder per acre), but these unthinned plots average only 16 percent more cubic volume. However, red alder on treatments with 80 red alder per acre had a larger average dbh and height than on plots with only 20 and 40 red alder per acre (table 5) (Miller et al. 1999).

Table 4. Number of trees per acre by species, 0.1 inch and larger, before and after thinning at plantation age 9 (from Miller et al. 1999).

Douglas-fir stand	Treatment no.	Before thinning			After thinning		
		DF	**RA**	**All**	**DF**	**RA**	**All**
0 N	1	1370	285	1870	302	0	303
200 N	5	1165	100	1410	307	0	307
20	2	1020	110	1250	297	22	320
40	3	970	230	1765	293	38	332
80	4	1125	185	1915	302	77	379
NT	6	1440	185	3290	1875	95	4023

Table 5. Average stand statistics per acre by species and treatment after thinning at plantation age 9, trees 0.1 in d.b.h. and largers (from Miller et al. 1999).

Douglas-fir stand	Treatment no.	Stems (number)			Dq (inches)			Height (feet)		Cubic volume total stem (cubic feet)		
		DF	RA	All	DF	RA	All	DF	RA	DF	RA	All
0 N	1	302	0	303	3,8	0	3,8	21,6	0	244	0	244
200 N	5	307	0	307	3,7	0	3,7	19,7	0	233	0	233
20	2	297	22	320	3,8	3,3	3,8	22,1	24,7	256	17	273
40	3	293	38	332	3,9	2,7	3,7	22	22,2	252	22	274
80	4	302	77	379	3,6	3,6	3,6	21,6	26,9	231	77	309
NT	6	1875	95	4023	1,2	1,2	0,9	9,4	14,4	285	55	359

4.1 PERIODIC ANNUAL DIAMETER INCREMENT

In the case of both Douglas-fir and all species combined, diameter PAI was significantly affected by treatment, year, and their interaction (all with p<0.0001). For all species combined, maximum diameter PAI of thinned plots occurred during the first growth period, whereas maximum diameter PAI of the unthinned plots peaked in the third measurement period (figure 2).

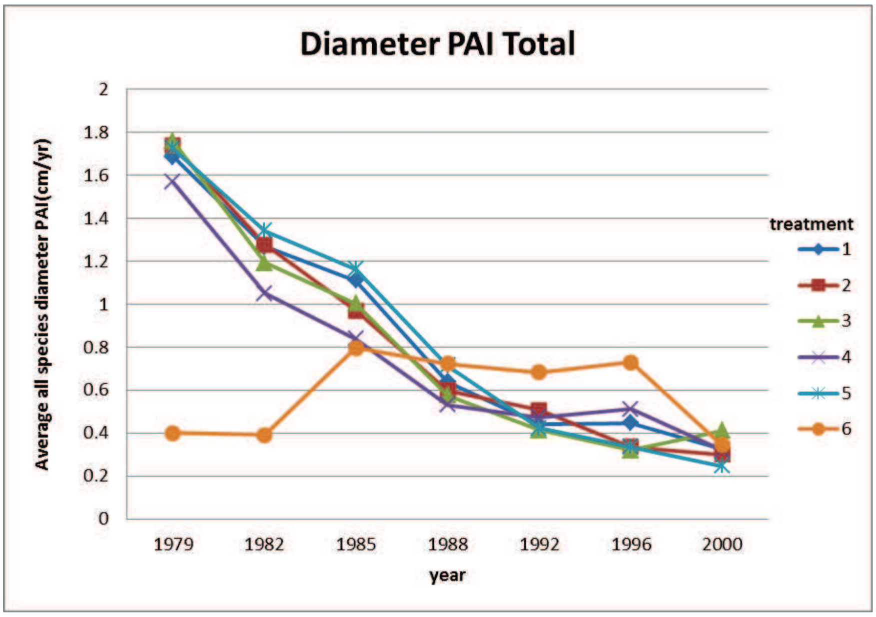

Figure 2: Total diameter PAI per treatment and year at the Risley Creek Douglas-fir/red alder study, all species combined.

In the case of only Douglas-fir, diameter PAI was significantly affected by treatment (p=0.0003), year (p<0.0001), and their interaction (p<0.0001). As for all species combinted, maximum diameter PAI in thinned plots occurred during the first growth period and and maximum PAI in unthinned plots occurred during the third growth period (figure 3).

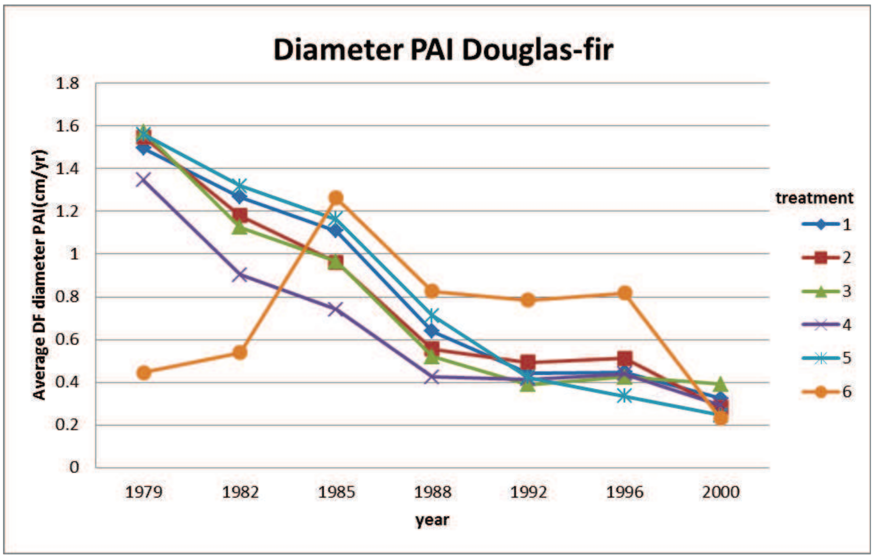

Figure 3: Douglas-fir diameter PAI per treatment and year at the Risley Creek Douglas-fir/red alder study.

4.2 PERIODIC ANNUAL HEIGHT INCREMENT

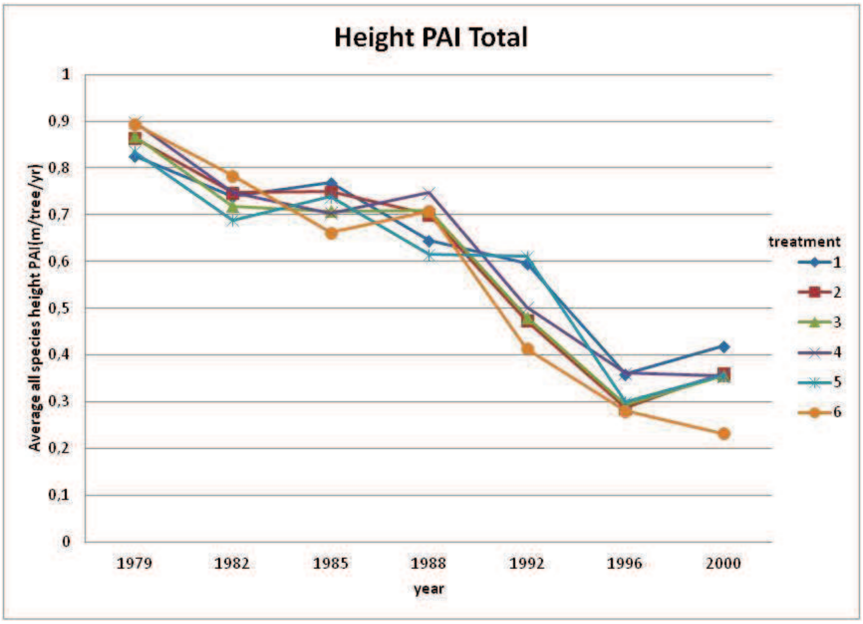

Figure 4. Height PAI averaged across all species by treatment and year ar the Risley Creek Douglas-fir/red alder study.

Douglas-fir periodic annual height increment was significantly affected by treatment (p=0.0423) and year (p<0.0001), but it was not significantly affected by their interaction (p=0.1542). Height PAI continually decreased over time (figure 5). The differences between treatments, while statistically significant, are relatively small, i.e., generally only about 0.1 m/yr between the fastest and slowest growing treatments.

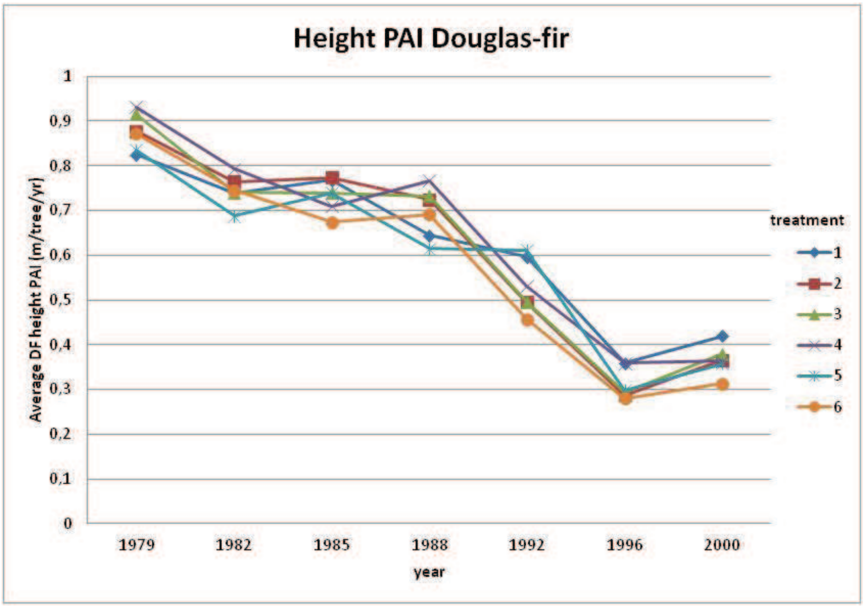

Figure 5: Douglas-fir height PAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

Red alder periodic annual height increment was significantly affected by treatment ($p=0.0005$), year ($p<0.0001$), and their interaction treatment&year ($p=0.0060$). Height PAI continually decreased over time (figure 6). The differences between treatments are greater than Douglas-fir height PAI, reaching as high as 0.35 m/yr.

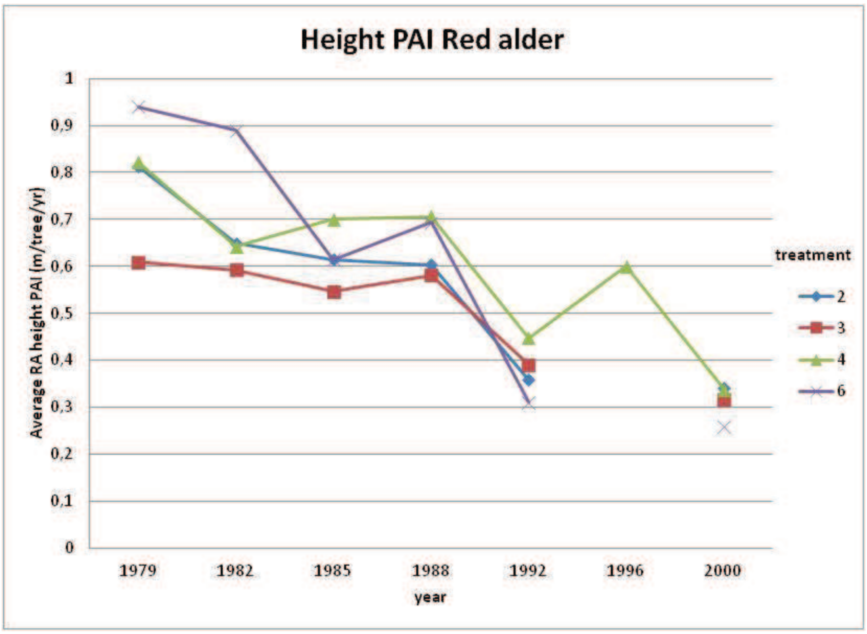

Figure 6: Red alder height PAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

4.3 PERIODIC ANNUAL TOP HEIGHT INCREMENT (LARGEST 100 TREES/HA BY DIAMETER)

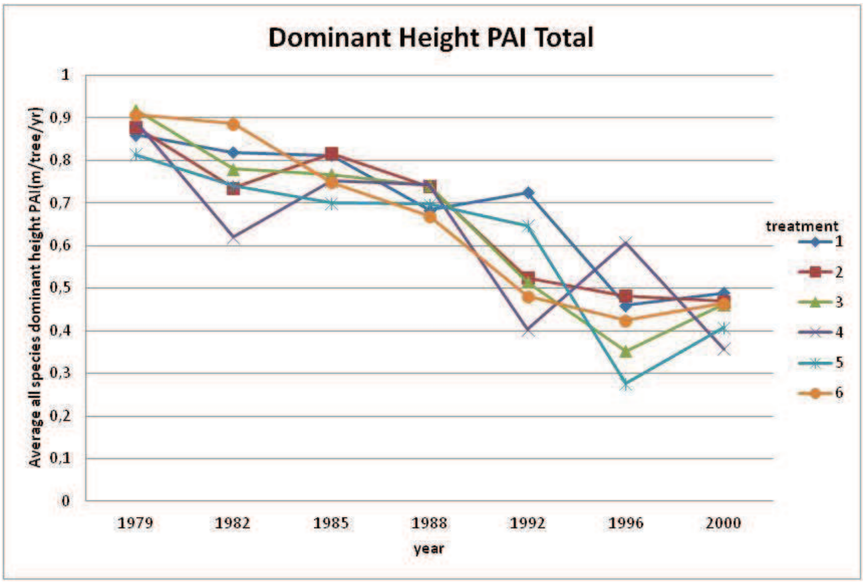

Figure 7: Total dominant height PAI per treatment and year at the Risley Creek Douglas-fir/red alder study.

Douglas-fir periodic annual top height increment was significantly affected by treatment (p=0.0027) and year (p<0.0001), but not by their interaction (p=0.2988). Maximum dominant height PAI of all treatments took place in the first growth period, and progressi,vely decreased over time. Minimum dominant height PAI occurred between last two growth periods in all treatments. During most of the study dominant height PAI generally decreasedfor all the treatments, except for an average increase of about 0.5 m in the last growth period (figure 8).

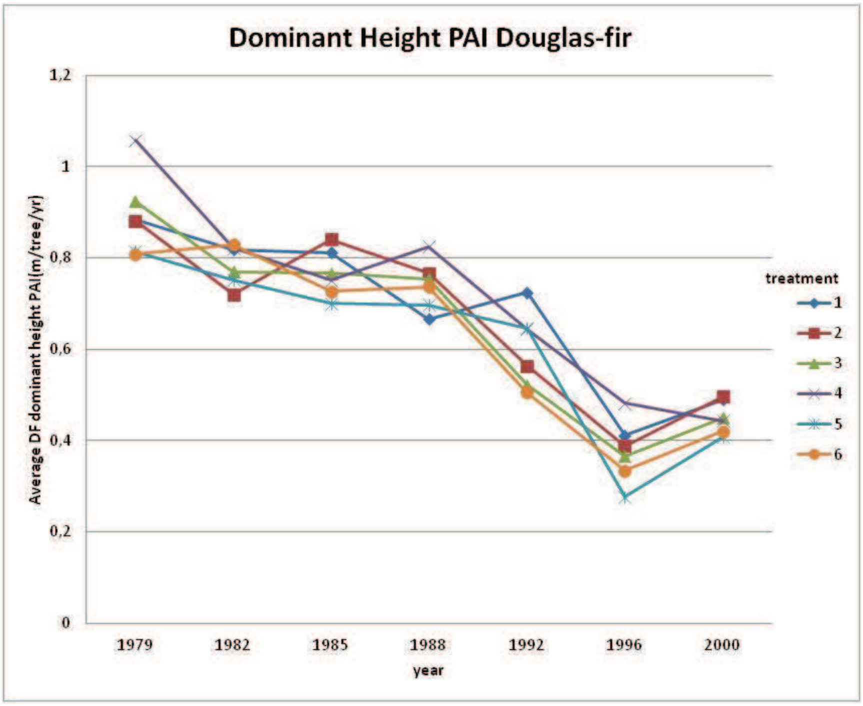

Figure 8: Douglas-fir dominant height PAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

Red alder periodic annual top height increment was significantly affected by treatment (p=0.0002), year (p<0.0001), and their interaction (p=0.0011). Maximum dominant height PAI of the four treatments which had red alder occurred during the first growth period, and it progressively decreased over time. For three of the four treatments, growth measurements were not available for the second-to-last growth period (figure 9).

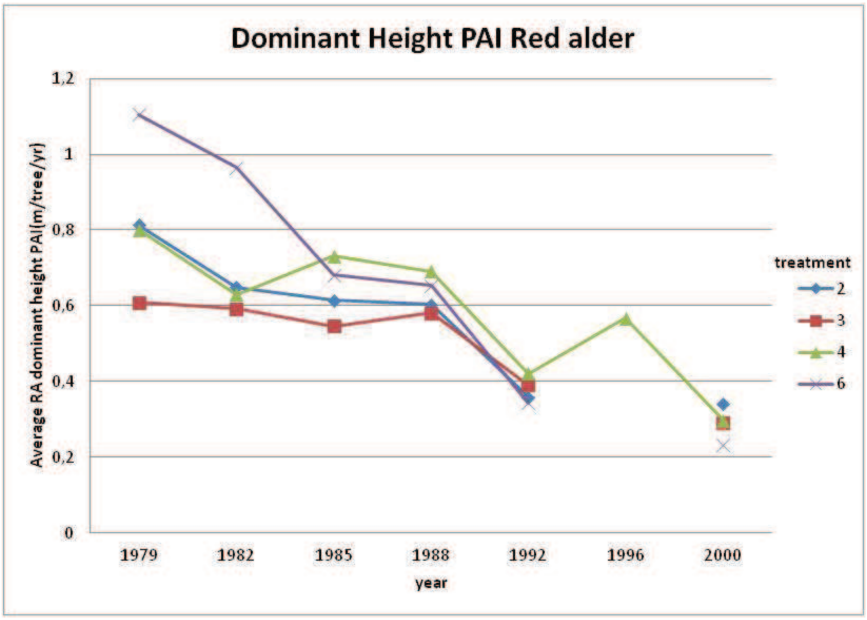

Figure 9: Red alder dominant height PAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

4.4 PERIODIC ANNUAL VOLUME INCREMENT.

Among the different levels of red alder retention (treatment 1, 2, 3 and 4), volume PAI of all species combined was significantly different among years ($p<0.0001$), but was not significantly affected by treatments ($p=0.8064$) or by the interaction between treatment and year ($p=0.7919$). Although volume PAI of all species combined peaked over time, it was not significantly different between treatments, whether they had 0, 20, 40 ord 80 red alder retained per acre (Figure 10).

Comparing thinned and unthinned plots, volume PAI of all species combined was significantly greater without thinning ($p<0.0011$), averaging 17.22 m^3/ac/yr, relative to 13.65 m^3/ac/yr on thinned plots with no retained alderand 13.51-14.09 m^3/ac/yr with 20-80 retained alder (figure 10).

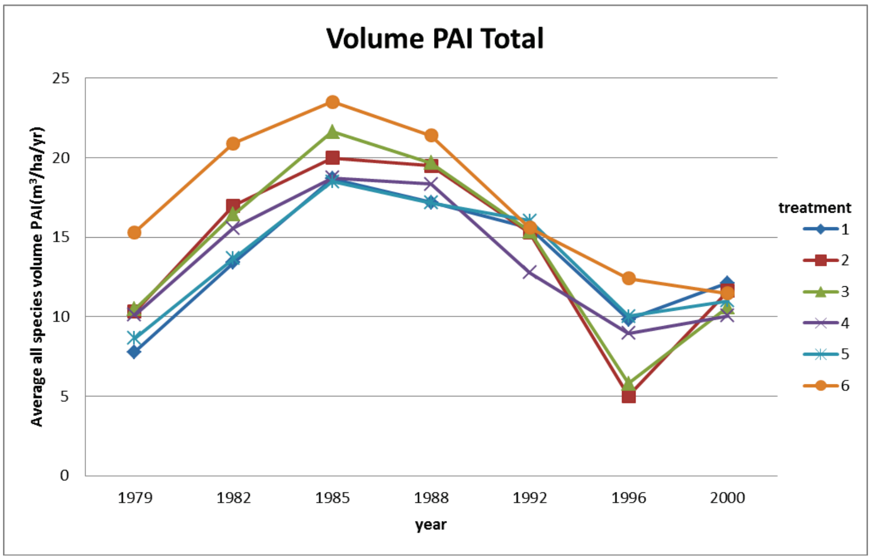

Figure 10: Total volume PAI per treatment and year at the Risley Creek Douglas-fir/red alder study.

Among the different levels of red alder retention (treatment 1, 2, 3 and 4), volume PAI of Douglas-fir only was significantly affected by treatment ($p<0.0001$) and by year ($p<0.0001$). Retention of red alder had a significant negative effect on Douglas-fir PAI, and all three alder retention levels resulted in diminished Douglas-fir PAI (p=<0.0016, <0.0050, and <0.0001 for the 20, 40, and 80 TPA treatments, respectively). Douglas-fir PAI averaged 13.65, 11.74, 11.97, and 8.30 m^3/ac/yr for 0, 20, 40, and 80 retained RA per ac, respectively, and only 8.27 m^3/ac/yr in the unthinned control treatment. The interaction effect between treatment and year was not significant ($p=0.4236$; figure 11).

Fertilization with 200 lbs. N per acre did not improve Douglas-fir PAI relative to the control ($p=0.9722$; treatment 1 versus treatment 5 in figure 11).

Pre-commercial thinning had a positive effect on Douglas-fir PAI (p<0.0001Unthinned plots produced a significantly lower Douglas-fir volume PAI than all other treatments except those with the heaviest alder retention (80 RA/ac; treatment 4 in figure 11).

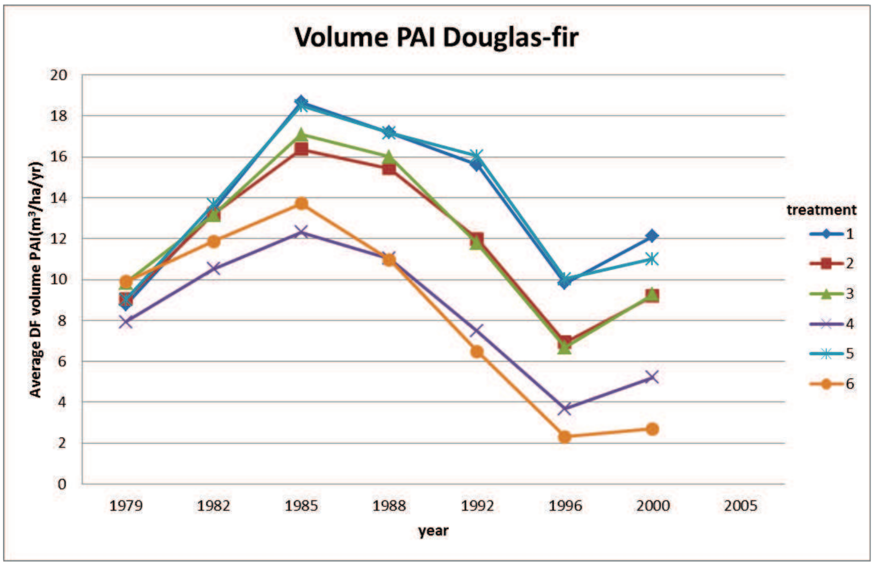

Figure 11: Douglas-fir volume PAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

4.5 PERIODIC ANNUAL MORTALITY BY VOLUME

Douglas-fir periodic annual mortality (PAM) by volume was not significantly affected by treatment ($p=0.3292$), but did differ significantly among years ($p<0.0001$). The interaction between treatment and year was not significant ($p=0.9074$). Maximum mortality of Douglas-fir occurred in treatment 6, the unthinned control treatment, and during the last two growth periods. Despite the lack of a significant treatment effect, a slight trend was evident for greater Douglas-fir mortality in unthinned plots and in thinned plots with the greatest alder retention (figure 12).

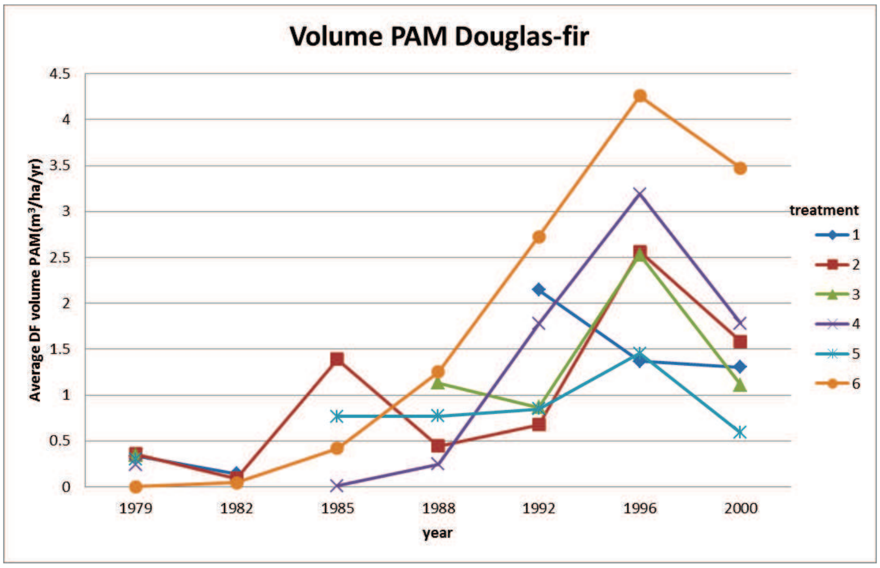

Figure 12: Douglas-fir volume PAM by treatment and year at the Risley Creek Douglas-fir/red alder study.

Red alder periodic annual mortality in volume was significantly affected by treatment (p=0.0004), year (p<0.0002) and their interaction (p=0<0.0001). Alder mortality was generally low, except that it exhibited a significant increase in the second-to-last growth period (figure 13).

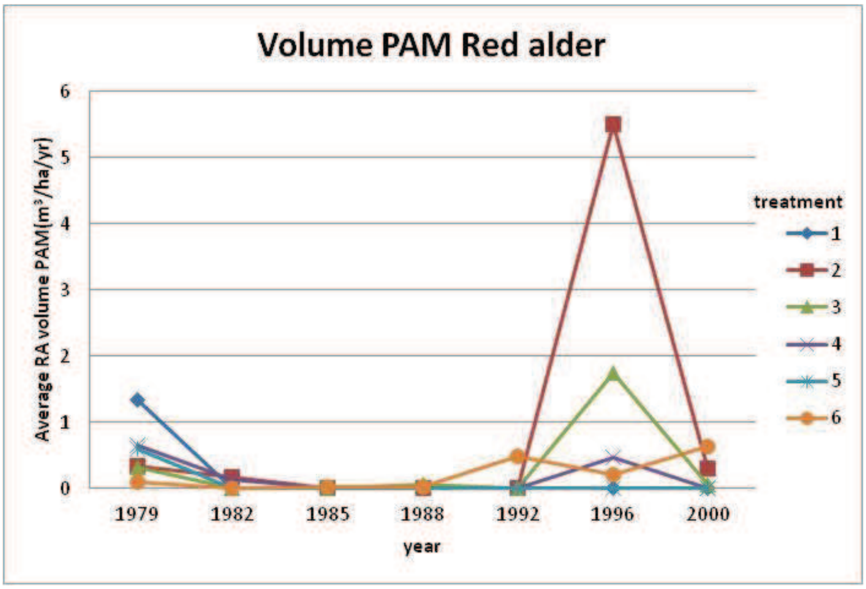

Figure 13: Red alder volume PAM by treatment and year at the Risley Creek Douglas-fir/red alder study.

4.6 FINAL STANDING CUBIC VOLUME

When total standing live volume in 2005 was analyzed, treatment had a significant effect (p=0.0047), with the unthinned treatment exhibiting significantly greater volume than all other treatments (figure 14). None of the other treatments had significantly different volumes among each other, though there was a slight trend of greater standing volume with greater alder retention.

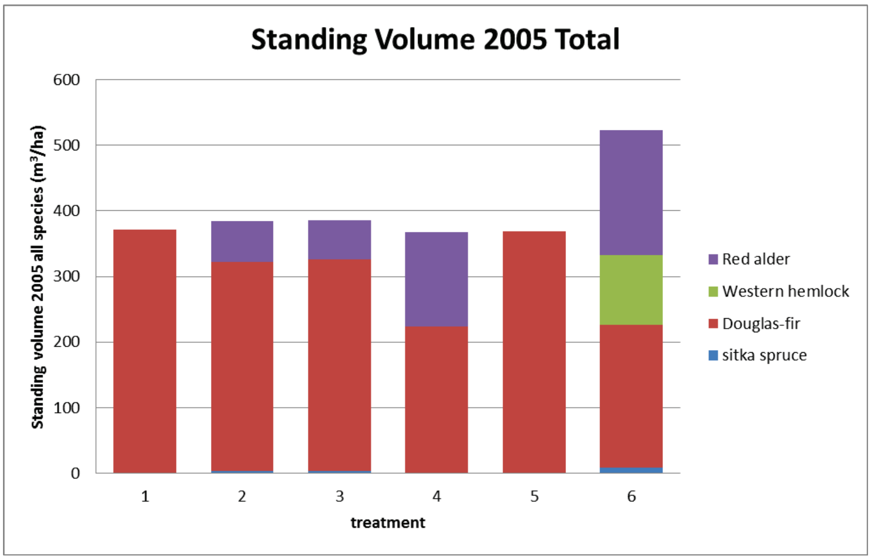

Figure 14: Total standing volume in 2005 at the Risley Creek Douglas-fir/red alder study.

In 2005, standing Douglas-fir volume was also significantly affected by treatment (p=0.0123), exhibiting greater volume on the thinned plots without no retained alder. The thinned treatment with no alder held significantly greater volume than the treatment with 80 retained alder per acre (p=0.0056) and than the unthinned plots (p=0.0045; figure 15).

Conversely, red alder standing volume increased with increasing red alder retention (figure 16).

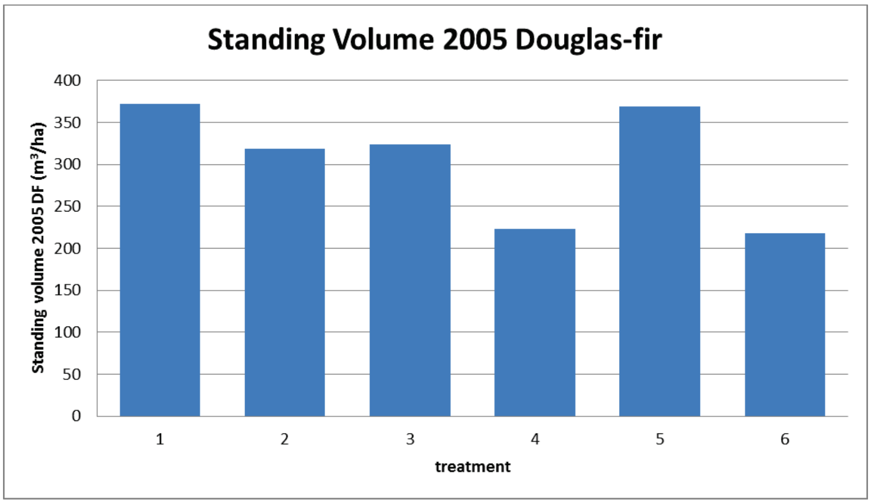

Figure 15: Douglas-fir standing volume in 2005 at the Risley Creek Douglas-fir/red alder study.

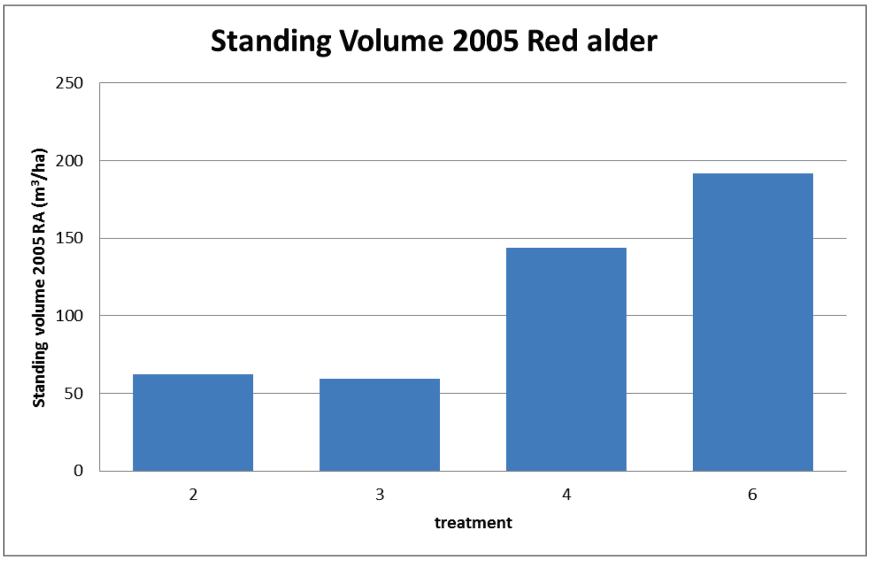

Figure 16: Red alder standing volume in 2005 at the Risley Creek Douglas-fir/red alder study.

4.7 TOTAL CUMULATIVE MORTALITY BY CUBIC VOLUME

Cumulative Douglas-fir mortality by volume differed significantly by treatment ($p = < 0.0001$) (figure 17). Unthinned plots had a significantly greater volume of cumulative mortality than any of the thinned plots ($p < 0.0001$). A similar treatment effect was observed for cumulative mortality of all species combined (figure 18).

There was not a significant difference between Douglas-fir mortality in fertilized versus unfertilized plots ($p = 0.8454$), or between plots with different red alder retention levels ($p = 0.0696$ for comparison between 0 and 80 RA trees per acre).

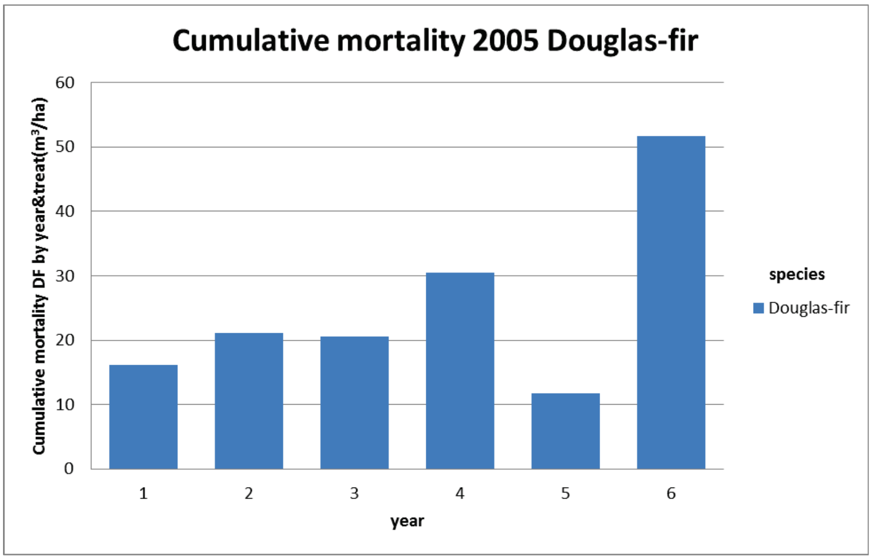

Figure 17: Douglas-fir cumulative cubic mortality at the Risley Creek Douglas-fir/red alder study.

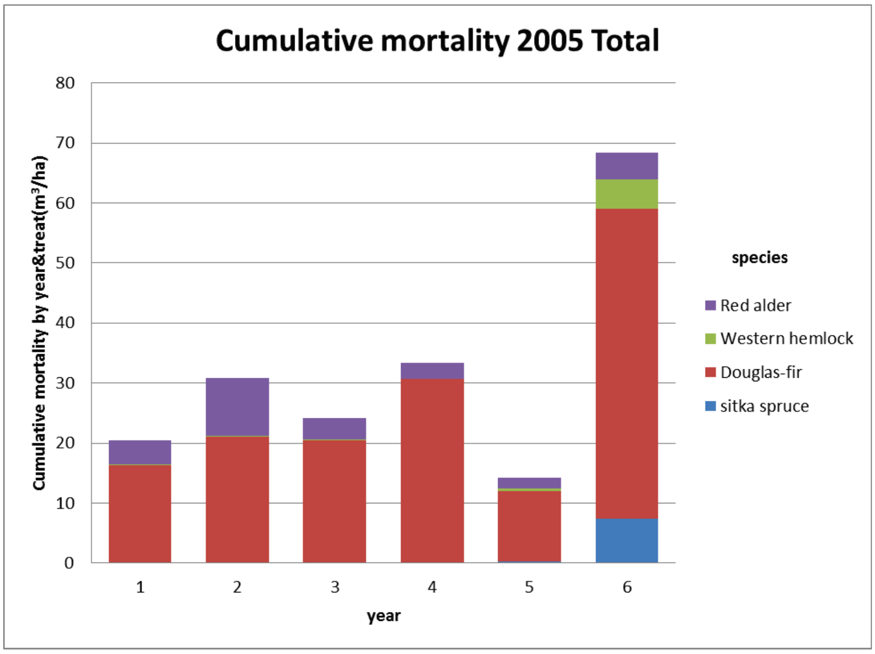

Figure 18: Total cumulative cubic mortality at the Risley Creek Douglas-fir/red alder study.

Red alder cumulative volume mortality was not significantly affected by treatment (p=0.2840) (figure 19).

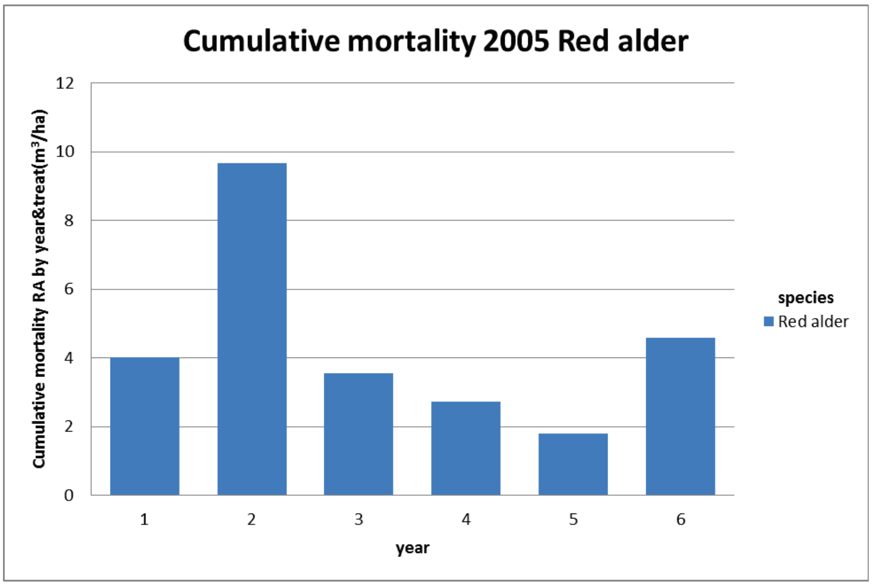

Figure 19: Red alder cumulative cubic mortality at the Risley Creek Douglas-fir/red alder study.

4.8 MEAN ANNUAL CUBIC VOLUME INCREMENT

Mean annual cubic volume increment for all species combined was significantly affected by treatment (p=0.0007) and year (p<0.0001) but was not significantly affected by their interaction (p=0.9907). Red alder retention level did not affect mean annual cubic volume increment of all species combined (figure 20).

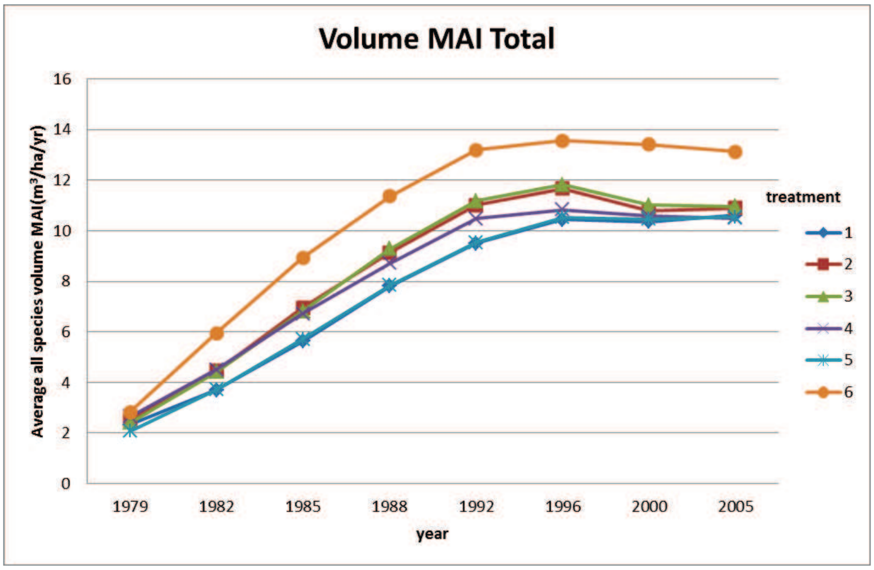

Figure 20: Total volume MAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

Mean annual cubic volume increment of Douglas-fir was significantly affected by treatment (p=0.0001) and year (p<0.0001), but not by their interaction (p=0.1113). With a greater retention of red alder and hence greater volume MAI of red alder, there is a corresponding decline in Douglas-fir volume MAI (figure 21).

Comparing the thinned and the unthinnedg plots, volume MAI of Douglas-fir was significantly affected by treatment (p<0.0001) and year (p<0.0001), but not by their interaction (p= 0.4495). Thinning out all but 300 Douglas-fir per acre resulted in a greater volume MAI of Douglas-fir (figure 21).

There is not a significant difference between fertilized and unfertilized plots (p=0.9275), so nitrogen did not appear to limit Douglas-fir productivity at Risley Creek.

Not surprisingly, red alder MAI increased with increasing red alder retention, and was greatest for the unthinned plots where alder grew at the expense of the other species (figures 21 and 22).

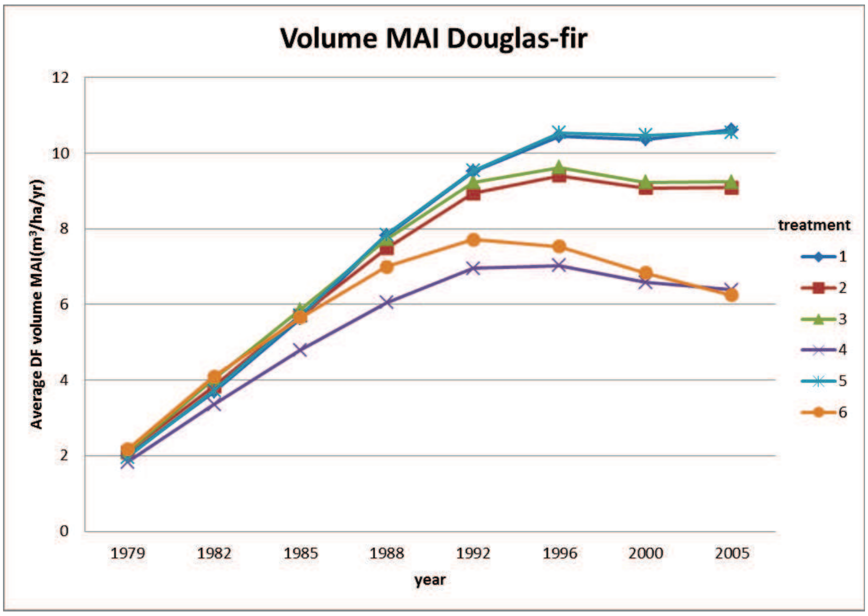

Figure 21: Douglas-fir volume MAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

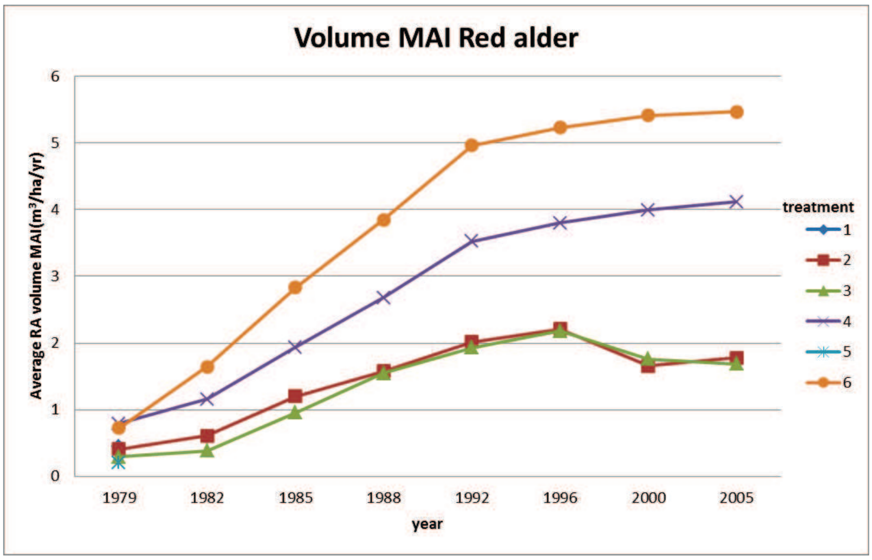

Figure 22: Red alder volume MAI by treatment and year at the Risley Creek Douglas-fir/red alder study.

4.9 MEAN ANNUAL CUBIC VOLUME MORTALITY

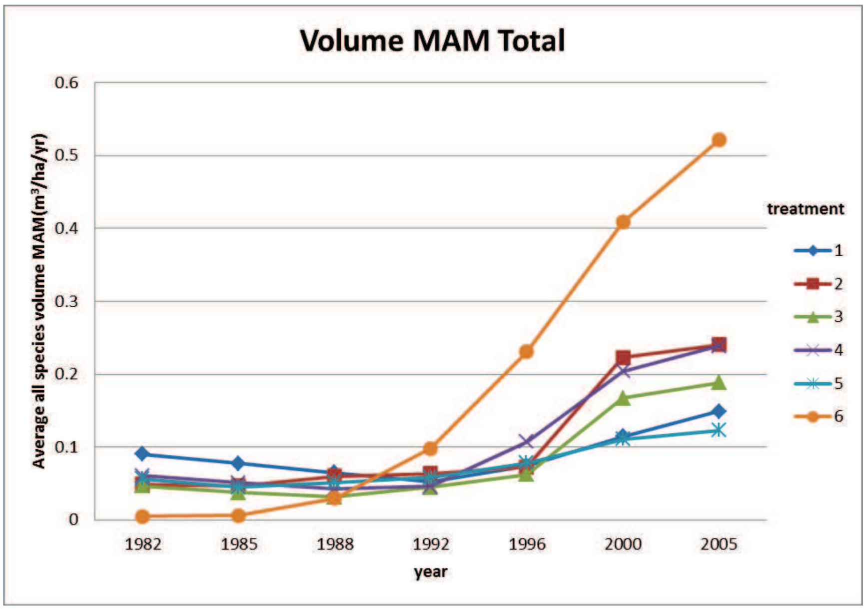

Figure 23: Volume MAM for all species combined by treatment and year at the Risley Creek Douglas-fir/red alder study.

Periodic annual volume mortality (MAM) for all species combined and for Douglas-fir only was significantly affected by treatment (p=<0.0001), year (p<0.0001), and their interaction (p=<0.0001) (figures 23 and 24).

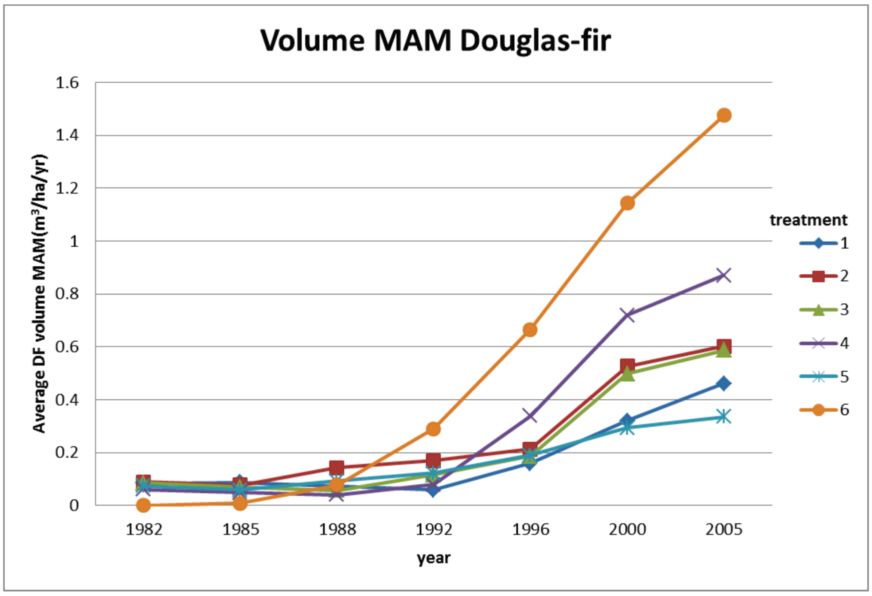

Figure 24: Douglas-fir volume MAM by treatment and year at the Risley Creek Douglas-fir/red alder study.

Red alder periodic annual volume mortality was significantly affected by treatment (p=<0.0001), year (p=<0.0001) and their interaction (p=<0.0001) (figure 25).

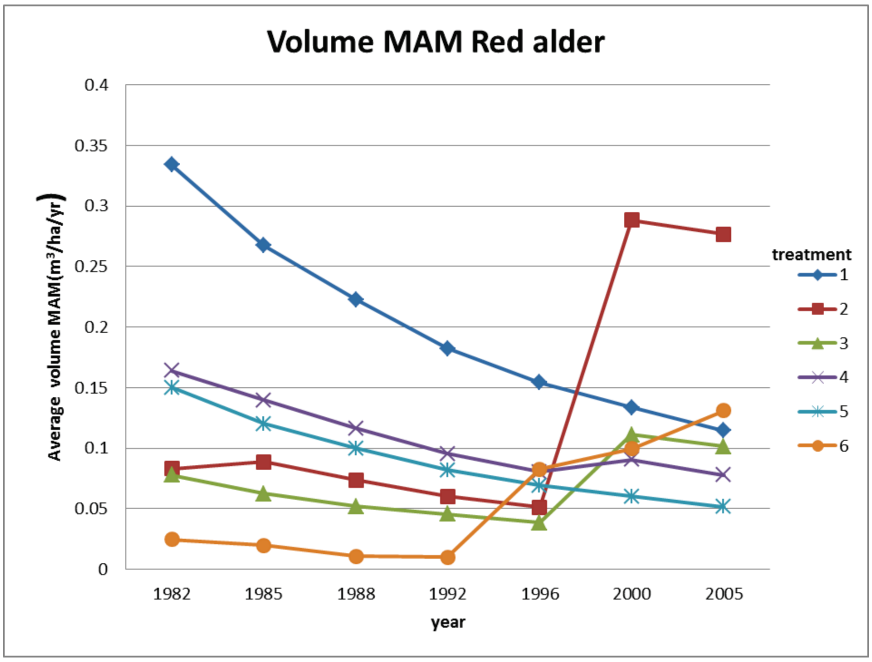

Figure 25: Red alder volume MAM per treatment and year at the Risley Creek Douglas-fir/red alder study.

5. DISCUSSION

The general conclusion after 25 years of stand development on the Risley Creek Douglas-fir/red alder study was that unthinned control plots produced the greatest cubic volume, and the pre-commercially thinned stands produced the least cubic volumes. As indicated by the periodic annual diameter increments, the tree sizes contributing to the unthinned control volume were much smaller than in the pre-commercially thinned stands.

Although red alder retained in the pre-commercially thinned Douglas-fir stands increased the total tree density (target of 320, 340 and 380 stems per acre), the volume of the alder was not additive because the alder accumulated volume at the expense of Douglas-fir trees that were outcompeted and often killed by overtopping red alder (Miller et al. 1999; Fig. 6). In fact, of the pre-commercially thinned plots, the greatest Douglas-fir volume was produced in those that retained 0 red alder trees. Increasing red alder retention led to diminishing Douglas-fir production, and though total volume production remained approximately constant across alder retention levels, there was a slightly positive trend with increasing alder retention. In short, the presence of red alder did not enhance growth of the 300 Douglas-fir trees per ac, but rather detracted from total Douglas-fir growth and survival. However, because the carrying capacity of a site for Douglas-fir is higher than for red alder, the fact that the total production remained constant across alder retention levels may indicate that some slight enhancement of Douglas-fir growth compensated for the typically lower volume production per ac that is typical of red alder on the same site.

Figure 26. Dead Douglas-fir (indicated by arrow) that tried to grow up through overtopping red alder crown (hardwoods with no leaves in the Risley Creek Douglas-fir/red alder study, Siuslaw National Forest.

The insignificant increase in total volume production with alder retention, as well as the significant increase in absence of thinning may be partially explained by the presence of Swiss needle cast (SNC) within the study area. Previous analyses have pointed to the extent to which Douglas-fir may be outcompeted by otherwise subordinate species in the presence of SNC (Zhao et al. 2014). Enhanced total production in these mixed-species plots may be partially due to this effect.

On average, fertilization with 200 lb nitrogen per acre is expected to stimulate an approximately 30 percent increase volume growth of Douglas-fir for 5-12 years after application. Conversely, with no possible benefit of nitrogen fixed by red alder, red alder retention would be expected to cause a reduction in growth, survival and yield of Douglas fir (Miller and others 2005). Miller et al. (1999) noted that volume growth in fertilized and unfertilized pure Douglas-fir plots was similar at Risley Creek, so nitrogen did not appear to be limiting Douglas-fir productivity at this site. Results from 2005 were consistent with their observed lack of a fertilizer treatment effect. In mixed plots of Douglas-fir and red alder, the presence of red alder was therefore expected to reduce Douglas fir yield. Although this effect was observed, the summed volume of both species was not significantly affected by treatment, in this case the level of red alder retention. Although Douglas-fir growth per unit initial growing stock could potentially have been enhanced by any nitrogen fixed by the retained red alder, the expectation of a positive effect of red alder on Douglas-fir growth and yield was negated by the lack of a response to direct fertilization. This lack of a growth response to fertilization with nitrogen was therefore consistent with the previous lack of a growth effect of red alder on Douglas-fir (Miller et al. 1999). Contrary to a growth enhancing effect, the growing space and resources used by the red alder reduced total Douglas-fir growth and yield, and with 80 red alder per acre, the greatest increase in Douglas-fir mortality and corresponding decrease in yield was observed. Even under the full range of 0 to 80 red alder per acre, however, the summed yield of both species combined was constant.

Thinning produced a reduction of stand volume, but the size of the trees was doubled, and the total volume of Douglas-fir was almost doubled. The utilizable volume produced by precommercially thinning the stand was therefore increased while the total production was reduced.

When ammonium nitrate was applied to Douglas-fir plantations, volume, diameter and height growth can all increase significantly (Miller and Tarrant 1983). Fertilized plots have been shown to produce 35 to 107 percent more cubic volume than unfertilized plots during the 15–year period after treatment. Similarly, volume growth of Douglas-fir increased by about 16-18% after fertilization in unthinned plots, and by about 20-22% in thinned plots (Chappell and others 1992). This growth response continued to be significant up to 8-16 years after treatment Li et al. (2007) noted that although fertilization is expected to increase stand-level diameter, basal area and volume PAI, the effect typically lasts only 8 years, after which the growth response starts to become insignificant. It is likely that the duration of growth response to N fertilization varies among sites for a number of reasons related to site characteristics such as inherent N availability, weather, and other factors influencing initial tree nutritional status and N mineralization and uptake.

5.1 STAND DEVELOPMENT IN UNTHINNED PLOTS

In unthinned plots, the density of trees is sufficiently high that suppression mortality is expected to lead to self-thinning and, depending on the vertical stratification by species and their relative shade tolerance, some species may experience more mortality and growth reduction than others. Because the top canopy layer in the unthinned stand was dominated by red alder (Fig. 27), competition from above reduced the growth of Douglas-fir, and further accelerated the mortality of smaller Douglas-fir that regenerated naturally (Miller et al. 1999).

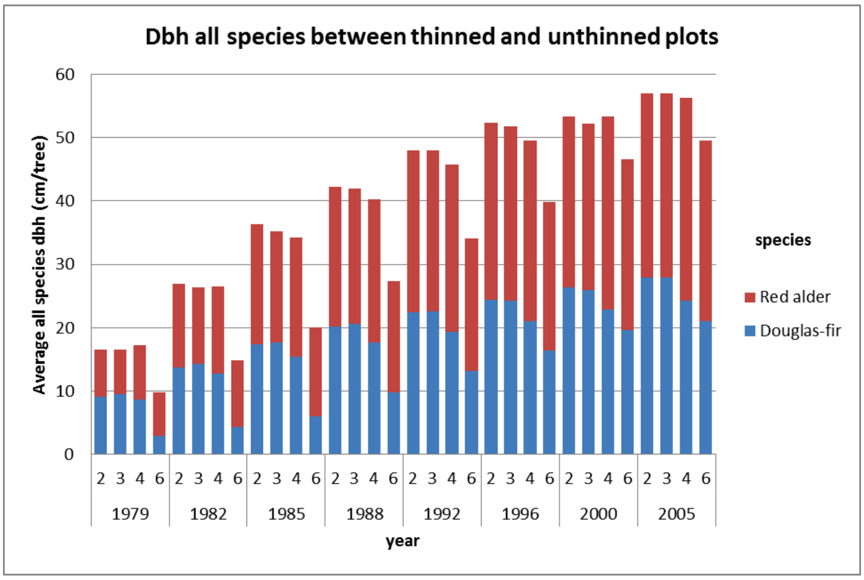

Figure 27. Dbh Douglas-fir and red alder in thinned (treat. 2, 3 and 4 with 40 and 80 RA/acre) and unthinned treatment (treat. 6).

5.2 EFFECT OF THINNING

Unthinned plots had high mortality, yet they also had more total volume than thinned plots at age 25 years. However, the lack of thinning hindered the growth and development of individual trees, so individual Douglas-fir trees in thinned plots had volumes that averaged 60% greater than in unthinned plots (Miller et al. 1999).

Diameter PAI was greater in thinned plots for the first three growth periods. By the fifth growth period diameter PAI of the unthinned plots had accelerated due to differentiation of a dominant layer of Douglas-fir and red alder and suppression mortality of the smallest trees (Fig. 28A).

Volume PAI of all species combined was greatest for unthinned plots. However, Douglas-fir volume PAI was greatest in thinned plots without red alder retention, so thinning to just 300 trees per acre of Douglas-fir improved volume PAI of Douglas-fir. Douglas-fir mortality was greatest in unthinned plots.

Standing volume at the time of last measurement was greatest for all species combined in the unthinned plots; however, the greatest volume of Douglas-fir was found in thinned plots with no red alder retention. Again, thinning to leave only Douglas-fir maximized growth and yield of Douglas-fir.

5.3 EFFECT OF FERTILIZING

Fertilized Douglas-fir plots did not grow any faster than unfertilized plots, reflecting the fact that growth in height, basal area, and volume of Douglas-fir did not differ between unfertilized and fertilized plots (Miller et al. 1999).

In a similar study installed in the Cascades Range of Washington, volume growth of Douglas-fir increased 27 percent in response to nitrogen fertilizerapplied at the rate of 200 lb N/acre (Miller, Anderson and Murray 2005). In the Cascades experiment, mortality volume was much lower in fertilized plots..

Large variation in the growth response to N fertilization has been observed among different stands. Peterson and Hazard (1990concluded that variation in growth response was influenced more by thinning than by physiographic provinceGrowth response to thinning and fertilization differed widely among different locations.

Fertilization did not improve Douglas-fir volume PAI in this study so we cannot say that there is a significant difference between fertilized and unfertilized plots. Likewise, standing live volume of Douglas-fir in the 2005 was not significantly difference between fertilized and unfertilized plots. Given this lack of growth response, it is not surprising that mortality of Douglas-fir was also not affected by fertilization.

5.4 EFFECT OF INCREASING NUMBERS OF RED ALDER

The yield of Douglas-fir was greatest in pure Douglas-fir plots, and this yield decreased with increasing red alder density, as was consistent with the 17-year results (Miller et al. 1999). In short, the competition effect of red alder overwhelmed any potentially positive effect of N fixation and/or improvement in litter quality.Standing volume of all species combined in 2005 did not differ between treatments with different levels of red alder retention (treatments 1 to 4); however, Douglas-fir volume increased in direct proportion to the reduction in red alder retention. Red alder is therefore growing at the expense of Douglas-fir. Douglas-fir mortality was not significantly affected by level of red alder retention.

5.5 RED ALDER VS. N-FERTILIZATION

Annual N fixation averages about 60 lb N/acre/year for well stocked red alder stands. Based on this average, the nitrogen fixed by 20, 40 and 80 red alder per acre was probably greater than 200 lb N/acre during all 17-yr period. Other studies estimate that the amount of N-fixation by red alder may have varied between 150 to 230 lb N/acre during all 17-yr period (Miller et al. 1999). Neitherred alder retention nor nitrogen fertilization improved the growth and yield of Douglas-fir at Risley Creek, and red alder reduced the growth and yield of the 300 Douglas-fir per ac in thinned plots. Nitrogen was therefore apparently not limiting to Douglas-fir productivity at this site.

6. CONCLUSIONS

- Thinned plots had lower total cubic volume of all species combined, but Douglas-fir volume was greater in the thinned plots. Thinning that includes removal of all other species favored growth and yield of Douglas-fir.

- Retaining 0, 20, 40, or 80 red alder per acre in addition to 300 Douglas-fir resulted in total volumes of all species combined that are not significantly different among these four treatments.

- Douglas-fir growth and yield declined with increasing red alder retention.

- Fertilization had no significant effect on Douglas-fir growth.

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APPENDIX

APPENDIX

1. TABLE OF DATASET AND SAS PROCEDUTE USED FOR ANALYSIS OF EACH RESPONSE VARIABLE.

Response	Response variable	Species	Dataset	SAS procedure
Dbh PAI	Dpai	All	TDINC1	MIXED
Dbh PAI	Dpai	Douglas-fir	DINC1	MIXED
Height PAI		All		
Height PAI	Hpai	Douglas-fir	HG1	MIXED
Height PAI	Hpai	Red alder	HG1	MIXED
H100 PAI		All		
H100 PAI	H100pai	Douglas-fir	HG1	MIXED
H100 PAI	H100pai	Red alder	HG1	MIXED
Volume PAI	Vpai	All	TOT4, SPEC3	MIXED
Volume PAI	Vpai	Douglas-fir	TOTDF, DF2, DF3	MIXED
Volume PAM	Vpam	All		
Volume PAM	Vpam	Douglas-fir	RMOUTPUT	MIXED
Volume PAM	Vpam	Red alder	RMOUTPUT	MIXED
2005 standing volume	V2005	All	TOT25	MIXED
2005 standing volume	V2005	Douglas-fir	TOTDF25	MIXED
Cumulative mortality	CumMort	All		
Cumulative mortality	CumMort	Douglas-fir	RC	MIXED

Cumulative mortality	CumMort	Red alder	RC	MIXED
Volume MAI	Vmai	All	TOT4	MIXED
Volume MAI	Vmai	Douglas-fir	TOTDF, DF2, DF3	MIXED
Volume MAM	Vmam	All		
Volume MAM	Vmam	Douglas-fir	RC	MIXED
Volume MAM	Vmam	Red alder	RC	MIXED

2. TABLE OF TESTS ON FIXED EFFECTS OF TREATMENT, YEAR, AND TREATMENT·YEAR INTERACTION

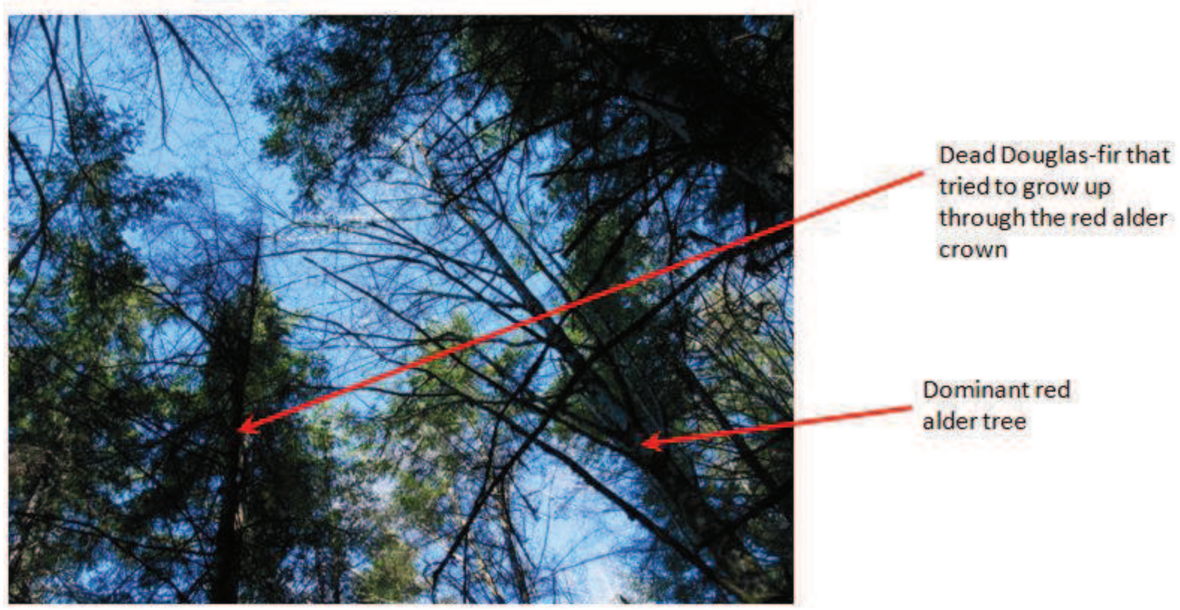
Response	Treatment		Year		Treatment·Year	
	F-statistic	P-value	F-statistic	P-value	F-statistic	P-value
DPAI, all	12.73	<0.0001	185.58	<0.0001	11.88	<0.0001
DPAI, DF	5.23	0.0003	138.50	<0.0001	9.43	<0.0001
HPAI, DF	2.42	0.0423	200.21	<0.0001	1.33	0.1542
HPAI, RA	7.23	0.0005	52.95	<0.0001	2.68	0.0060
H100PAI, DF	3.99	0.0027	80.04	<0.0001	1.15	0.2988
H100PAI, RA	8.40	0.0002	47.47	<0.0001	3.33	0.0011
VPAI, ALL T(1-4)	0.33	0.8064	25.21	<0.0001	0.70	0.7919
VPAI, ALL T(1-4,6)	4.20	0.0042	26.52	<0.0001	0.66	0.8686
VPAI, DF T(1-4)	30.40	<0.0001	40.05	<0.0001	1.05	0.4236
VPAI, DF T(1-5)	24.80	<0.0001	43.79	<0.0001	0.96	0.5270
VPAI, DF T(1-4,6)	14.41	<0.0001	22.00	<0.0001	0.81	0.7172
VPAM, DF	1.19	0.3292	5.76	0.0001	0.61	0.9074
VPAM, RA	12.92	0.0004	14.35	0.0002	18.24	<0.0001
V2005, ALL	6.15	0.0047				
V2005,DF	4.79	0.0123				
CUMMORT, ALL						

CUMMORT, DF	6.46	<0.0001	29.50	<0.0001	1.78	0.0212
CUMMORT, RA	1.28	0.2840	1.24	0.2984	0.45	0.9902
VMAI, ALL	6.38	0.0007	193.23	<0.0001	0.39	0.9907
VMAI, DF T(1-4)	24.12	<0.0001	99.37	<0.0001	1.50	0.1113
VMAI, DF T(1-5)	17.08	<0.0001	108.32	<0.0001	1.18	0.2826
VMAI, DF T(1-4,6)	11.42	<0.0001	56.46	<0.0001	1.02	0.4495
VMAM, DF	6.54	<0.0001	24.01	<0.0001	1.76	0.0236
VMAM, RA	2.69	0.0303	0.48	0.8231	0.60	0.9305

3. METRIC EQUIVALENTS.

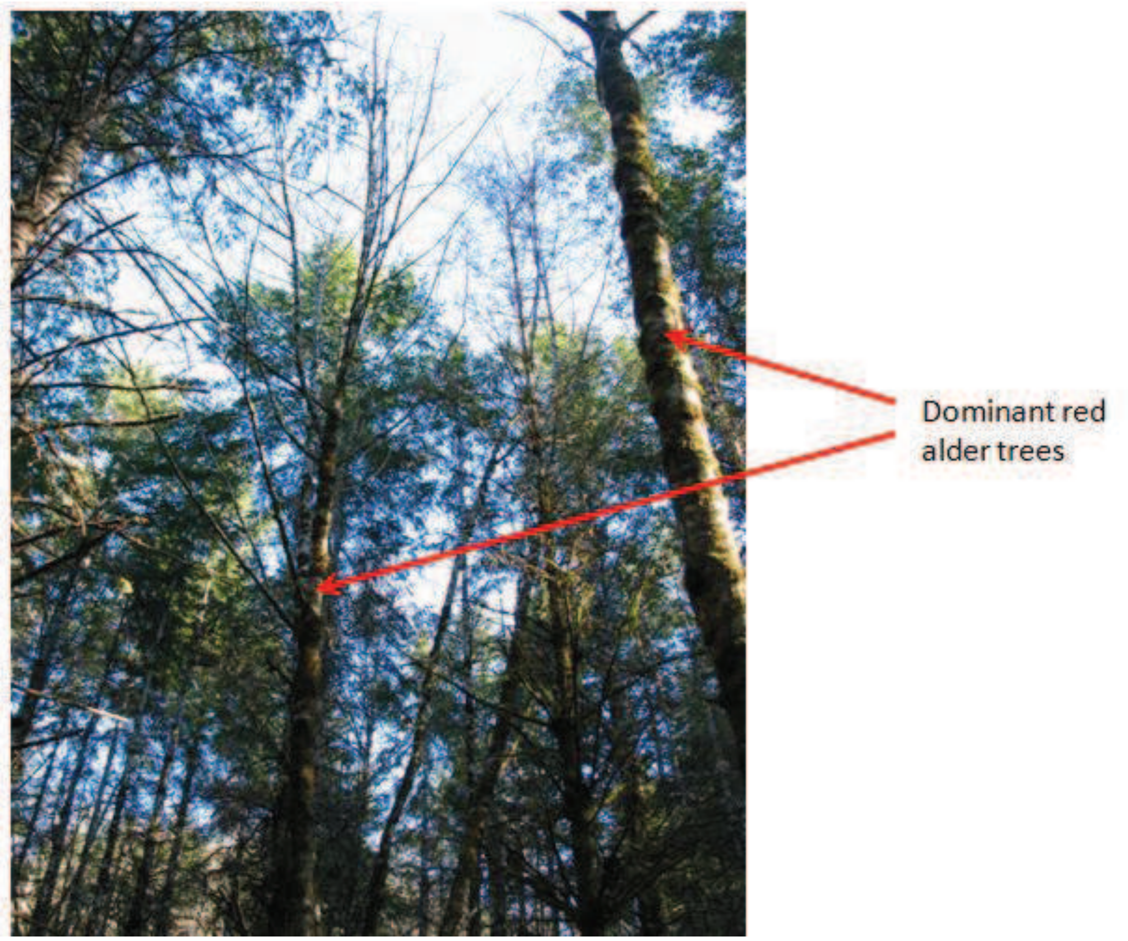
1 inch (in) = 2.54 centimeters
1 foot (ft) = 0.3048 meter
1 square foot (ft2) = 0.0929 square meter
1 cubic foot (ft3) = 0.028 cubic meter
1 acre = 0.4047 hectare
1 square foot per acre = 0.2296 square meter per hectare
1 cubic foot per acre = 0.06993 cubic meter per hectare
1 pound (lb) = 453.592 grams
1 gallon (gal) = 3.785 liters

4. PICTURES



Picture 1. Mixed stand of Douglas-fir and red alder(treatment 4).

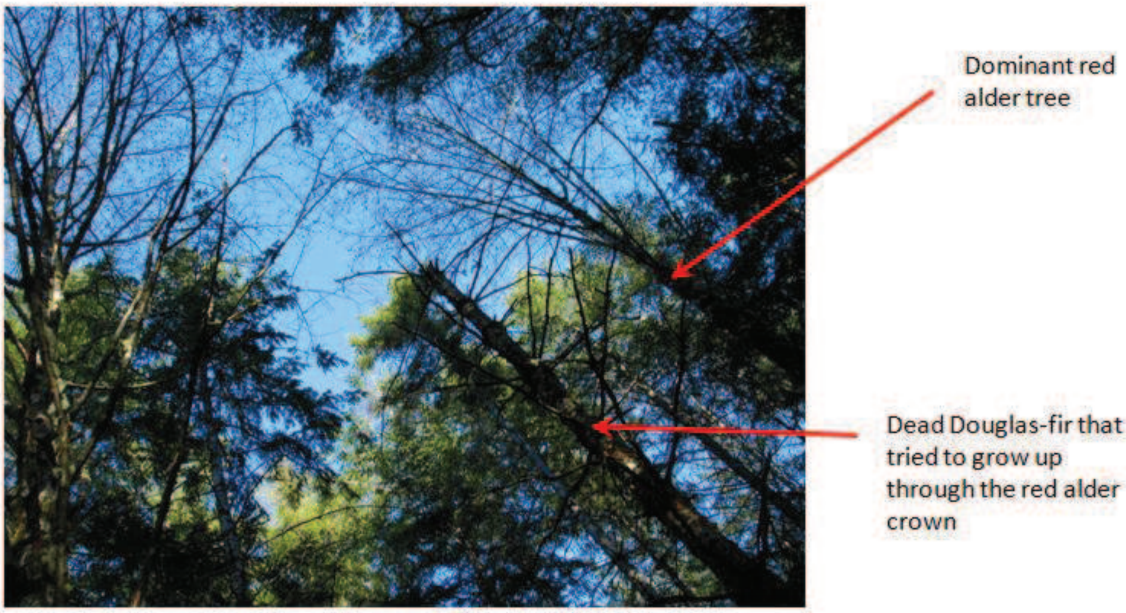
Picture 2. Mixed stand of Douglas-fir and red alder (treatment 3).



Picture 3. Mixed stand of Douglas-fir and red alder (treatment 3).

Picture 4. Pure Douglas-fir stand (treatment 1).

Picture 5. Pure Douglas-fir stand (treatment 1).



Picture 6. Mixed stand of Douglas-fir and red alder (treatment 2).

5. SAS CODES

This program reads the edited Risley Creek field data, fits height-diameter equations for all species-plot-year combinations with a sufficient number of observations, imputes missing heights with fitted equations if available or with regional height-diameter curves (Garman et al. 1995) if no equation could be fitted for a given species-plot-year combination, estimates total cubic volume above a 1-ft stump for each tree, and then writes the tree data and plot-level data (by species) to an EXCEL file.

```
/*  Input data from EXCEL  */

proc import out=risl

datafile="C:\Users\pajaresj\Desktop\ayuda_Doug\check.xls"
   dbms=excel2000 replace;
   getnames=yes;
   sheet='check';
   /* variables include:
       plot sp tree newtag d79 h79 hlc79 st79 d82 h82 hlc82 st82 d85 h85 hlc85 st85 d88 h88 hlc88 st88 d92 h92 hlc92 st92
                        d96 h96 hlc96 st96 d00 h00 hlc00 st00 d05 h05 hlc05 st05
   */
run;

proc means data=risl;
   title 'Summary of original Risley dataset prepared for Juan 4 Feb 2015';
run;

/*  Tally trees by species:
    98  sitka spruce
    202 Douglas-fir
    263 Western hemlock
    351 Red alder
    747 Black cottonwood
    920 Willow
*/
proc sort data=risl;
  by sp;
run;
proc summary data=risl;
  by sp;
  var plot;
  output out=sptal n(plot)=sptal;
run;
/*  Separate out data by year of measurement  */
data ris79;
  set risl;
  /* Write trees with no initial dbh in 1979 - perhaps ingrowth trees that appear later */
  if d79=. or d79=0 then put plot sp tree d79 h79;
  if st79=0;
  d=d79;
  h=h79;
  /* Assume height to live crown is 0 feet in 1979 */
  if hlc79=. then hlc=0;
  else if hlc79>=0 then hlc=1*hlc79;

  status=st79;
  year=79;
  keep plot sp tree newtag year d h hlc status;
```

```
run;
proc means data=ris79;
  title 'Summary of 1979 Risley data';
run;
data ris82;
  set risl;
  if st82=0;
  d=d82;
  h=h82;
  hlc=1*hlc82;
  status=st82;
  year=82;
  keep plot sp tree newtag year d h hlc
status;
run;
data ris85;
  set risl;
  if st85=0;
  d=d85;
  h=h85;
  hlc=1*hlc85;
  status=st85;
  year=85;
  keep plot sp tree newtag year d h hlc
status;
run;
data ris88;
  set risl;
  if st88=0;
  d=d88;
  h=h88;
  hlc=1*hlc88;
  status=st88;
  year=88;
  keep plot sp tree newtag year d h hlc
status;
run;
data ris92;
  set risl;
  if st92=0;
  d=d92;
  h=h92;
  hlc=1*hlc92;
  status=st92;
  year=92;
  keep plot sp tree newtag year d h hlc
status;
run;
data ris96;
  set risl;
  if st96=0;
  d=d96;
  h=h96;
  hlc=1*hlc96;
  status=st96;
  year=96;
  keep plot sp tree newtag year d h hlc
status;
run;
data ris00;
  set risl;
  if st00=0;
  d=d00;
  h=h00;
  hlc=1*hlc00;
  status=st00;
  year=00;
  keep plot sp tree newtag year d h hlc
status;
run;
data ris05;
  set risl;
  if st05=0;
  d=d05;
  h=h05;
  hlc=1*hlc05;
  status=st05;
  year=05;
  keep plot sp tree newtag year d h hlc
status;
run;
```

/* Merge data for all years */

```
data risley;
  set ris79 ris82 ris85 ris88 ris92 ris96 ris00
ris05;
  if sp=747 or sp=920 or sp=. then do;
    put plot sp year d h;
    delete;
  end;
run;
/*  Tally number of trees in each species x
year x plot combination  */

proc sort data=risley;
  by sp plot year;
run;
proc summary data=risley;
  by sp plot year;
  var sp;
  output out=ntrees n(sp)=ntrees;
run;
/*  Tally number of height trees in each
species x year plot combination  */
proc sort data=risley;
  by sp plot year;
run;
proc summary data=risley;
  by sp plot year;
  var h;
  output out=nht n(h)=nht;
run;
/* Tally number of missing heights of each
species in each plot and year  */
data miss;
  set risley;
  if d>0 then do;
    if h=0 or h=.;
  end;
run;
proc sort data=miss;
 by sp plot year;
run;
proc summary data=miss;
  by sp plot year;
  var d;
  output out=nmiss n(d)=nmiss;
run;
/*  Fit nonlinear H-D equations by plot and
year and species  */
proc nlin data=risley method=marquardt
noprint outest=gout maxiter=150;
  by sp plot year;
  parameters g1=20
         g2=-8;
  model h = 1.37 + g1*exp(g2/d);
  der.g1 = exp(g2/d);
  der.g2 = g1*exp(g2/d)*(1/d);
run;
*/
data ristree;
  merge risley par;
  by sp plot year;
  /* Delete trees with no dbh  */
  if d<=0 then delete;
  /* Define variable hmeas as measured
height and assing height if tree
    has a measured height */
  if h ne . and h ne 0 then htmeas=h;
  /* Estimate height of all trees with Risley
specific regression equations,
    including trees with either measured or
missing heights
  */
  if g1>0 then do;
   if d>0 then htreg=1.37 + g1*exp(g2/d);
   else if d<=0 then htreg=.;
   /* Assign height as htreg if tree has no
measured height */
   if h=. or h=0 then h=htreg;
  end;
  /* Estimate height of all trees with
Garman et al. (1995) regional equations,
    including trees with either measured or
missing heights
```

```
  */
  if sp=98 then htgar= (1.37 +
(65.27757*(1-exp(-
0.012361*d))**0.967921) ) ;
  else if sp=202 then htgar= (1.37 +
(84.92352*(1-exp(-
0.010853*d))**0.936797) ) ;
  else if sp=263 then htgar= (1.37 +
(60.87614*(1-exp(-
0.021948*d))**1.078265) ) ;
  else if sp=351 then htgar= (1.37 +
(37.36855*(1-exp(-
0.023400*d))**0.761640) ) ;

  /* If tree has neither a measured height
or a height estimated from Risley specific
     regression equation, then estimate
height with Garman et al. (1996) regional
equation
  */
  if g1<=0 or g1=. then do;
    if h=. or h=0 then h=htgar;
  end;
  /* Convert year code to actual year */
  if year<79 then year=year+2000;
  else year=year+1900;
run;
/* Plot measured or estimated heights on
dbh by species to verify that all estimated
   (and measured) heights are >0
*/
proc sort data=ristree;
  by sp;
run;
proc plot data=ristree;
  by sp;
  plot h*d;
run;
```

```
/* Assess relationship between Garman
et al. (1995) estimates (htgar) and
regression estimates (htreg),
   between Garman et al. (1995) estimates
(htgar) and direct height measurements
(htmeas), and between regression
   estimates (htreg) and direct height
measurements (htmeas)
*/
proc plot data=ristree;
  by sp;
  plot htgar*htreg;
  plot htgar*htmeas;
  plot htreg*htmeas;
run;
/* Fit nonlinear htreg-htgar regression to
scale Garman equation to Risley data for
each
   species in each year across plots */
proc sort data=ristree;
  by sp year;
run;
proc nlin data=ristree method=marquardt
noprint outest=bout maxiter=150;
  by sp year;
  parameters b1=1
             b2=1;
  model htreg = b1*(htgar**b2);
  der.b1 = htgar**b2;
  der.b2 = b1*(htgar**b2)*log(htgar);
run;
/* Merge tree data with paramter
estimates from htreg-htgar regressions,
calibrate
  height estimates from htgar equations,
and estimate tree volumes */
proc sort data=ristree;
  by sp year;
run;
proc sort data=hpar;
  by sp year;
```

```
run;
data ristrees;
  merge ristree hpar;
  by sp year;
  /* Adjust height if height is estimated
with htgar from Garman equations */
  if hmeas=0 or hmeas=. then do;
    if htreg=0 or htreg=. then do;
      if b1>0 and b2>0 then
h=b1*htgar**b2;
      else if sp=351 and year=2000 then
h=2.40*htgar**0.68;
      else put plot sp year tree d h htmeas
htreg htgar;
    end;
  end;

  /*  Compute individual tree volumes  */
  if sp=98 then v =(1/35.3147)*(10**(-
2.550299))*((d/2.54)**1.835678)*((h/0.30
48)**1.042599); /* sitka spruce */
  else if sp=202 then do;
    if h<1.38 then h=1.38;
    v1=0.001168*(( ((h/0.3048)-4.5)/
(d/2.54) )**0.265430)*(
((d/2.54)**2)*((h/0.3048)-4.5) ) ; /*
Douglas-fir  */
    dibs=0.989819*(d/2.54);
    dib=0.903563*(d/2.54)**0.989388;
    pi=3.14159;

v2=(pi*dibs**2/175616)*(729+81*(dib/dib
s)**(2/3) + 297*(dib/dibs)**(4/3)
+265*(dib/dibs)**2);
    v=(1/35.3147)*(v1+v2);
  end;
  else if sp=263 then v=(1/35.3147)*exp(-
6.3054647 +
0.014978752*(d/2.54))*((d/2.54)**2.03372
86)*((h/0.3048)**1.0849) ; /* Western
hemlock  */
  else if sp=351 then
v=(1/35.3147)*(0.04969879 +
0.00247940*((d/2.54)**2)*(h/0.3048)); /*
Red alder  */
   /* Write out tree if height is negative */
  if h ne . and h<0 then put sp plot year d h;
  keep plot year sp tree newtag d h hlc
status htmeas htreg htgar v;
run;
/*  Plot measured or estimated heights on
dbh by species to verify that all estimated
   (and measured) heights are >0
*/
proc sort data=ristree;
  by sp;
run;
proc plot data=ristree;
  by sp;
  plot h*d;
run;
/*  Compute total cubic volume in cubic
meters per plot for each species in each
year on each plot  */
proc sort data=ristrees;
  by plot year sp;
run;
proc summary data=ristrees;
  by plot year sp;
  var v;
  output out=vols sum(v)=plotvol;
run;
/* Expand volume per plot to volume per
hectare  */
data volpha;
 set vols;
 vph=plotvol*(1/0.081);
run;
proc print data=volpha;
  title 'Plot volumes in cubic meters per ha
by species';
  var plot year sp vph;
```

```
run;
/* Compute total volume per hectare of all
species for given plot and year  */
proc sort data=volpha;
  by plot year;
run;
proc summary data=volpha;
  by plot year;
  var vph;
  output out=totvols sum(vph)=totvph;
run;
proc plot data=totvols;
  by plot;
  plot totvph*year;
run;
/*  Write tree data to EXCEL file  */
proc sort data=ristrees;
  by plot sp tree year;
run;

proc export data=ristrees
outfile="C:\Users\pajaresj\Desktop\ayuda_
Doug\sasDoug.xls"
  dbms=excel2000 replace;
  sheet='tree volumes';
run;
/*  Compute PAIs and MAIs for each
species in each plot and year  */
proc sort data=volpha;
  by sp plot year;
run;
data spinc;
  set volpha;
  by sp plot year;
  if first.sp or first.plot then put sp plot
year;
  else do pai=(vph-vph0)/(year-year0);
    pai=(vph-vph0)/(year-year0);
          paiyr=year0;
  end;
  mai=vph/(year-1970);
  maiyr=year;
  keep sp plot paiyr pai maiyr mai;
  vph0=vph;
  year0=year;
  retain vph0 year0;
run;
data paisp;
  set spinc;
  if pai ne .;
  year=paiyr;
  keep sp plot year pai;
run;
data maisp;
  set spinc;
  year=maiyr;
  keep sp plot year mai;
run;
proc sort data=paisp;
  by sp plot year;
run;
proc sort data=maisp;
  by sp plot year;
run;
data specinc;
  merge paisp maisp;
  by sp plot year;
run;
proc print data=specinc;
  title 'PAI and MAI by plot, species, and
year';
run;
/*  Compute PAIs and MAIs for all species
lumped in each plot and year  */
data plotinc;
  set totvols;
  by plot year;
  if first.plot then do;
    put plot year;
  end;
  else do;
    pai=(totvph-totvph0)/(year-year0);
```

```
            paiyr=year0;
   end;
   mai=totvph/(year-1970);
   maiyr=year;
   keep plot paiyr pai maiyr mai;
   totvph0=totvph;
   year0=year;
   retain year0 totvph0;
run;

data paitot;
   set plotinc;
   if pai ne .;
   year=paiyr;
   keep plot year pai;
run;
data maitot;
   set plotinc;
   year=maiyr;
   keep plot year mai;
run;
proc sort data=paitot;
   by plot year;
run;
proc sort data=maitot;
   by plot year;
run;
data totinc;
   merge paitot maitot;
   by plot year;
run;
/*  Assess general trend of an increase in
individual DF tree volume through year
2000  */
data plot1df;
   set ristrees;
   if sp=202 and plot=1;
run;
proc plot data=plot1df;
   plot v*year;
run;
```