Universidad de Valladolid
Campus de Palencia

ESCUELA TÉCNICA SUPERIOR
DE INGENIERÍAS AGRARIAS

Máster en Ingeniería de Montes

Quantifying the differential competitive effect of hardwood and coniferous species on Douglas-fir growing in southwestern Oregon mixed conifer forests (USA)

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Septiembre 2016

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0. ABSTRACT (RESUMEN)

A lo largo de la historia, la gestión forestal ha estado generalmente centrada en la investigación de las masas monoespecíficas, dada su menor complejidad de manejo frente a las masas mixtas.

Esta dinámica se ha visto modificada en los últimos años, cobrando cada vez más interés las masas mixtas debido a los potenciales beneficios que presentan frente a las masas monoespecíficas; como que promueve la biodiversidad consiguiendo de esta manera masas con mayor resiliencia y resistencia frente agentes patógenos, ya sean bióticos o abióticos.

Recientes estudios han demostrado que en ciertas masas mixtas, en las cuales se presentan diferentes mezclas de especies complementarias, pueden incrementar la producción con respecto a las masas monoespecíficas.

Basándose en este camino, el Forestry Intensified Research (FIR) se centró en la investigación de manejo de las masas mixtas del Suroeste de Oregón (EE.UU.). Como fruto de estos proyectos se desarrolló ORGANON, un modelo de crecimiento para diferentes especies en este tipo de bosques.

ORGANON predice el crecimiento diametral de una serie de especies a través de ciertas variables que caracterizan el rodal y propio árbol; como son: 1) tamaño del árbol (diámetro), 2) vigor del árbol (radio de corona), 3) productividad del rodal (índice de sitio) y 4) el efecto de la competencia.

En nuestro proyecto, con el objetivo principal de llegar a conocer la dinámica de las masas mixtas del Suroeste de Oregón, hemos estudiado las diferentes interacciones de competencia que se dan entre las distintas especies y con ellas mismas.

Partiendo del modelo citado anteriormente, ORGANON, desarrollado por el Dr. David Hann durante finales de la década de los 70 y principios de los 80, vamos a estudiar si existen diferencias en el crecimiento diametral del Abeto Douglas (*Pseudotsuga menziesii*) al crecer en masas mixtas dominadas por frondosas o masas mixtas dominadas por otras coníferas.

El primer análisis realizado fue probar la hipótesis nula de no diferencias significativas entre el crecimiento diametral del Abeto Douglas entre las masas monoespecíficas y las masas mixtas. Con un nivel de significancia de $\alpha=0.05$, el análisis concluyó que el crecimiento diametral entre las masas monoespecíficas y las masas mixtas era significativamente diferente (p-valor= 0.0459).

El segundo análisis estadístico partió del cálculo de una nueva variable: la masa foliar, la cual posteriormente se introducirá en el modelo. De esta forma, las variables que median el efecto competitivo en el modelo original de ORGANON fueron modificadas introduciendo en ellas la masa foliar. Para calcular esta nueva variable se utilizaron las regresiones no lineales desarrolladas por Jenkins (2004) en un trabajo previo.

Se optó por utilizar dicha variable, ya que variables anteriormente utilizadas como el área basimétrica o el área basimétrica de los arboles más grandes que el árbol sujeto, implicaban que cada unidad de área basimétrica impone el mismo grado de competencia, sin tener en cuenta la composición de especies de la parcela, de esta nueva forma, especies con un alto porcentaje de masa foliar por unidad de área basimétrica presentarán un efecto competitivo más fuerte en el Abeto Douglas en igualdad de condiciones.

Se desarrollaron y evaluaron las siguientes 5 ecuaciones para los distintos individuos de Abeto Douglas: 0) Reducida o base, ecuación simple sin variables que midan el efecto de la competencia, 1) Con las variables dependientes del área basimétrica y 2, 3 y 4) distintas combinaciones utilizando tanto las variables dependientes del área basimétrica como de la nuevas variables dependientes de la masa foliar.

Los resultados obtenidos indicaron que particularmente el uso de la masa foliar total de la parcela mejoraba los modelos con una reducción del error cuadrático medio de un 18%, con lo que se puede concluir que esta variable establece una buena representación de los efectos de la competencia en las masas mixtas de Suroeste de Oregón.

INTRODUCTION

1. INTRODUCTION

Intensive wood production has generally been focused on pure stands, whose high productivity, relative simplicity, and predictable management requirements and timelines have been the focus and beneficiary of long-term research (FAO, 2000). More recently, additional focus has been put on the advantages provided by mixed species forests.

Mixed species forests are associated with many positives, particularly in contrast to monospecific plantations, and are of increasing interest to the public. Mixed species forests promote biodiversity at both the stand and the landscape levels, and this biodiversity provides the forest with higher levels of resistance and resilience to environmental hazards, both biotic and abiotic (Bravo-Oviedo, 2014).

In addition, some recent studies have demonstrated that in some cases mixed species forests can boost productivity relative to monospecific stands (Bielak, Dudzinska, & Pretzsch, 2014). This increase in productivity of mixed species forests has been a focus of recent research, with efforts focused on trying to find the combinations of species able to boost productivity relative to pure stands.

With this objective in mind, during the late 1970s and early 1980s the Forestry Intensified Research (FIR) project identified a number of silvicultural challenges to managing the mixed-conifers forests of Southwest Oregon. As part of the FIR effort, David Hann was funded to develop ORGANON, a growth and yield model for this forest type (Hann , 2011).

ORGANON predicts the five year diameter growth of Douglas–fir from a group of predictor variables that characterize the tree and the stand. These predictor variables account for:

1) tree size (D; Diameter);

2) tree vigor (CR; crown ratio);

3) stand productivity (SI; site index); and

4) the competitive effects of neighboring trees.

For this, a wide range of competition variables or indices have been used including basal area of trees with larger D than the subject tree (BAL), stand total basal area (BA) (Hann and Larsen, 1990), crown closure at the top of the subject tree (CCH), and tree crown surface area (TCSA) (Bravo, Hann, & Maguire, 2001.).

The challenge in mixed species stands is to test for differential competition or benefits from trees of different species on one another. In many of the mixed conifer stands in the Klamath Mountain of southwestern Oregon, the stand are predominantly

Douglas-fir with varying mixtures of other conifer and hardwood species, and Douglas-fir is typically the most commercially valuable species in the mix.

Any negative or positive effects of other species in the stand are therefore important for designing silvicultural strategies to meet stand management objectives.

The specific objectives of this study are: 1) to test the different competitive effects of the main hardwood and coniferous species growing with Douglas-fir in the mixed species forests of southwestern Oregon; and 2) to test the relative efficacy of tree foliage mass in explaining competition effects on Douglas-fir, relative to basal area. If species differ in the amount of leaf area they hold per unit basal area then they would be expected to have different competitive effects per unit basal area.

OBJECTIVES

2. OBJECTIVES

- The main objective of this study is to test for differences in the growth response of Douglas-fir to competitive effects of the main hardwood and coniferous species growing with Douglas-fir in the mixed species forests of southwestern Oregon.

Sub-objectives include:

- To test the relative efficacy of foliage mass of other species as a predictor of their relative competitive effect on the diameter growth of Douglas-fir.

MATERIAL AND METHODS

3. MATERIAL AND METHODS

3.1. Location

The study is located in southwestern Oregon (figure 1). Forests cover more than 12 million of Oregon´s 25 million-hectare land base or 48 percent of the state´s total landmass. (Oregon Forest Resources Institute, 2015-2016).

Figure 1. Map of United States of America and area of study.

Specifically, the stands sampled for this study are located in a rugged series of mountain ranges called Klamath-Siskiyou Mountains.

This ecoregion is considered an area of global botanical significance by the World Conservation Union (IUCN) (Wagner, 1997) and also an area of exceptional ecological interest (Whittaker, 1960) mainly due to strong regional climatic, topographic and edaphic gradients. Forests in this region are notable for their great variety of conifer and schlerophyllous hardwood species, making it one of the most complex forests of western North America.

The stand elevations range from about 290 meters to more than 1550 meters. Five major coniferous species dominate the overstory of the mid-elevation zone, with their relative importance varying by local moisture and temperature regime.

The five major species include Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), grand/white fir (*Abies concolor* x *Abies grandis*), sugar pine (*Pinus lambertiana*), and incense cedar (*Calocedrus decurrens*).

In addition, other conifer species are often found in individual stands at bordering elevational zones or in wetter or drier habitats, for example, western hemlock (*Tsuga heterophylla*), Pacific silver fir (*Abies amabilis*), western redcedar (*Thuja plicata*), Shasta red fir (*Abies magnifica* x *Abies procera*), Jeffrey pine (*Pinus jeffreyi*), western white pine (*Pinus monticola*), and knobcone pine (*Pinus attenuata*). Numerous hardwood species such as California black oak (*Quercus kelloggii*), Oregon white oak (*Quercus garryana*), and several species of schlerophyllous hardwoods are also common, including tanoak (*Lithocarpus densiflorus*), chinkapin (*Chrysolepis chrysophylla*), madrone (*Arbutus menziesii*), and canyon live oak (*Quercus chrysolepis*).

Figure 2 shows the localizations of the study stands. This figure also distinguishes the type of stands by color: pure Douglas-fir stands (red color), mixed-conifer stands (yellow color) and mixed hardwood stands (green color). This classification will be defined below in the section on Stand Analysis (Section 3.3).

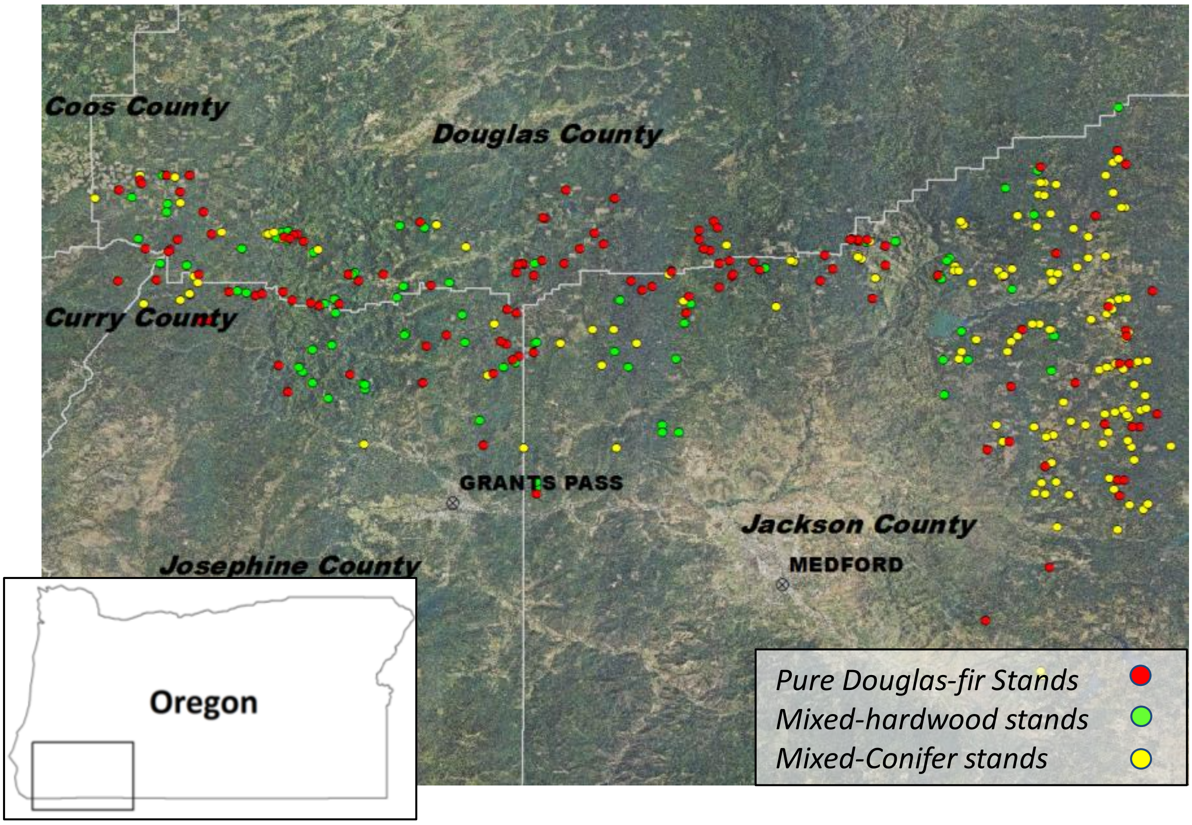


Figure 2. Geographic distribution of the Stands.

The climate of this ecoregion is affected by some major influences, including steeply dissected topography, proximity to the Pacific Ocean, and the seasonal variations in upper-level westerly winds that result in a pronounced summer drought.

In the north part of this ecoregion, where the study stands are located, annual precipitation is generally greater, summers are cooler, and the length of the dry season is shorter.

Mean annual precipitation decreases strongly from the coast inland, from values over 180 cm, through values of 80, and from approximately 150 cm in the central Siskiyou Mountains, to values below 50 cm in the interior valleys (Whittaker, 1960).

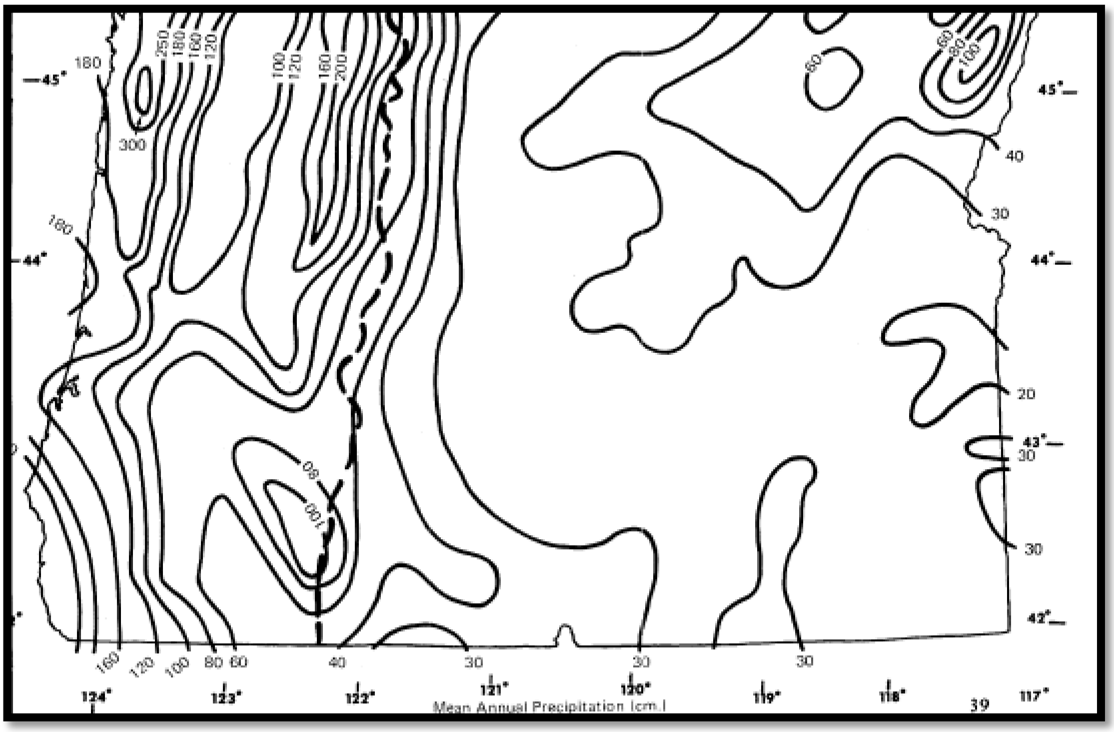


Figure 3. Mean annual precipitation in Oregon (U.S. Weather Bureau 1960)

Mean annual precipitation decreases strongly from the coast inland, from values over 180 cm, through values of 80 to probably 150 cm in the central Siskiyou´s mountains, to values below 50 cm in the interior valleys (Whittaker, 1960).

The wettest months are December or January normally, during which about 35-45 percent of total annual precipitation falls. The next wettest month is November with 12-16 percent of total annual precipitation. About 45-55 percent of the yearly total precipitation occurs during the period between November and January. The driest months are July and August, the most intense period of summer drought (Hobbs, 1992).

3.2. Plot design

For this analysis, the original southwestern Oregon dataset used for constructing the first version of ORGANON was analyzed to test the hypothesis of how the presence and competitive pressure of different species influences the diameter growth of Douglas-fir (Bravo 2001).

The plot design is composed of four to ten sample points located at the apexes of equilateral triangles with 46-meter sides (figure 4). At each sample point, four nested subplots were used to sample trees of varying size classes:

- A 20 BAF (Basal Area Factor = 20 ft^2/ac) variable radius subplot was used to measure all trees greater than 20 cm in diameter at breast height (dbh).
- A fixed area subplot of radius 4.75 m was used to measure all trees with dbh greater than 10.15 cm and less than or equal to 20 cm.
- A fixed area subplot of radius 2.37 m was used to measure all trees with dbh less than or equal to 10.15 cm.

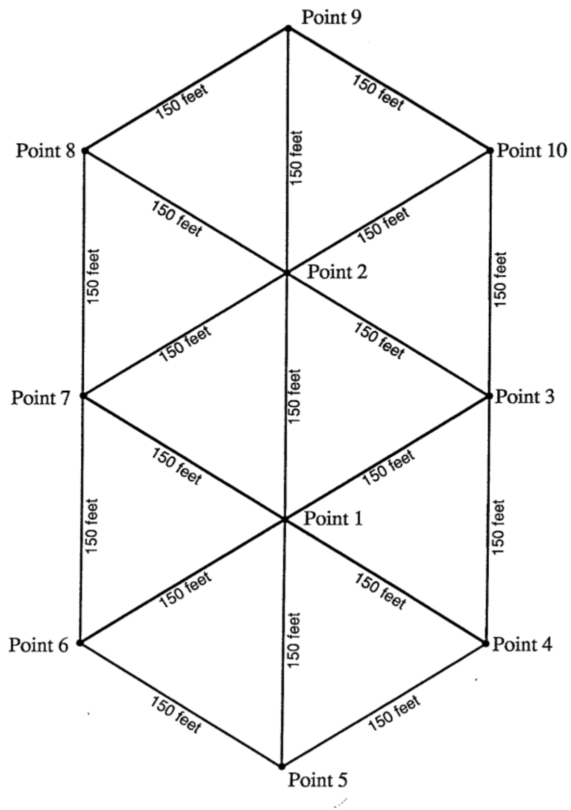


Figure 4. Basic Plot design (Department of Forest Management, Hann D. W., 1983)

Each sample plot provided unbiased estimates of permanent plot growth components by applying various techniques for backdating to the start of the previous 5-yr growth period.

The following measurements were taken at the end of the 5-year growth period on every tree: 1) Diameter at breast height (DBH); 2) Total height (H); and 3) Height to crown base (HCB). Backdating of dbh to the start growth of the previous 5-year period was accomplished by coring every live tree capable of receiving an increment borer.

After the basic tree variables were taken, a number of tree and stand variables were calculated for the start of the growth period, including: 1) Basal area for each stand (BA); 2) Crown Ratio (CR); 3) Basal area of larger trees than the subject tree (BAL); and 4) Douglas-fir site Index (SI).

3.3. Stand Analysis

The dataset used for this work was collected between 1981 and 1983. A total of 391 randomly selected stands form the dataset, with the overstory made up of 27 species: 15 conifers species and 12 hardwood species.

The stands were classified according to the percentage of basal area contributed by each species:

1) Pure Douglas-fir stands: ≥ 80% of the total basal area in Douglas-fir.
2) Pure non-Douglas-fir stands: ≥ 80% of the total basal area in species other than Douglas-fir.
3) Mixed-species stands.

Of the 391 stands comprising the complete dataset, 129 stands were classified as pure Douglas-fir (33.2%), 239 stands as mixed-species stands (61.4%) and only 23 stands as pure non-Douglas-fir stands (5.4%). Due to the small number of plots of the latter type, they were not considered in this analysis.

The mixed-species stands were divided further into two subsets:

1) Mixed-conifer stands: non-Douglas-fir species were dominated by conifers (159 stands).
2) Mixed-hardwood stands: non-Douglas-fir species were dominated by hardwoods (80 stands).

Figure 5 shows the distribution of each type of stand and its percentage.

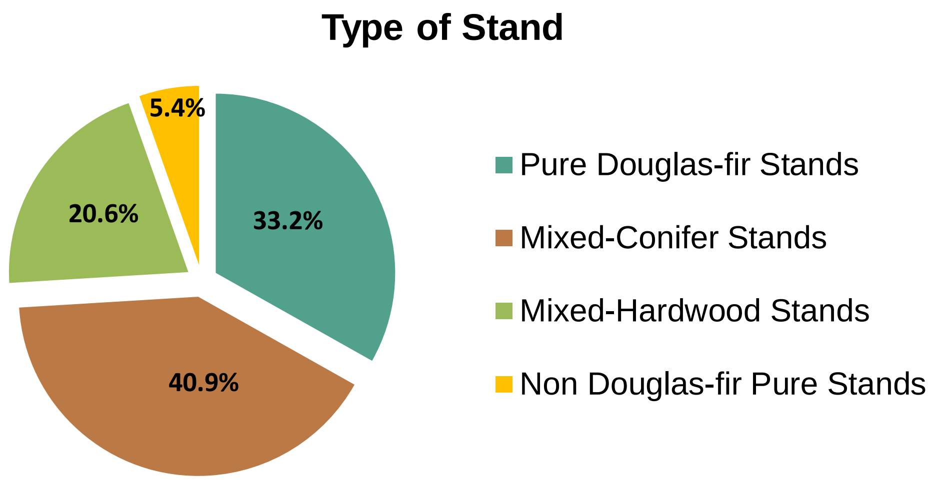


Figure 5. Compositional classes of plots sampled in the southwestern Oregon growth and yield project.

Summary statistics for the Pure Douglas-fir stands, Mixed-conifer stands and Mixed-hardwood stands are provided in Table 1.

Table 1. Summary of the stands attributes of the data set.

Type of Stand		Basal area (m^2/ha)			Trees per hectare		
	n	mean	sd	range	mean	sd	range
Pure Stands Douglas-fir	129	18.94	5.81	0.35-29.8	1542.4	1580.0	56.6-11745.7
Mixed-Conifer stands	159	16.33	6.31	0.72-31.41	2022.9	1756.5	189.8-10595.7
Mixed-hardwood stands	80	13.89	5.95	1.03-26.46	3456.1	2387.0	300.3-11674.6

Figure 6 shows one example of the classification of stands according to the percentage of basal area contributed by each species (m^2/ha).

Stands number 4, 9 and 418 correspond to the pure Douglas-fir stands. Stands number 2, 38 and 230 correspond to the mixed-conifer stands. Stands number 49, 252 and 409 correspond to the mixed-hardwood stands.

The great variety of conifer and schlerophyllous hardwood species of this ecoregion is demonstrated in figure 6, 12 species in 9 plots.

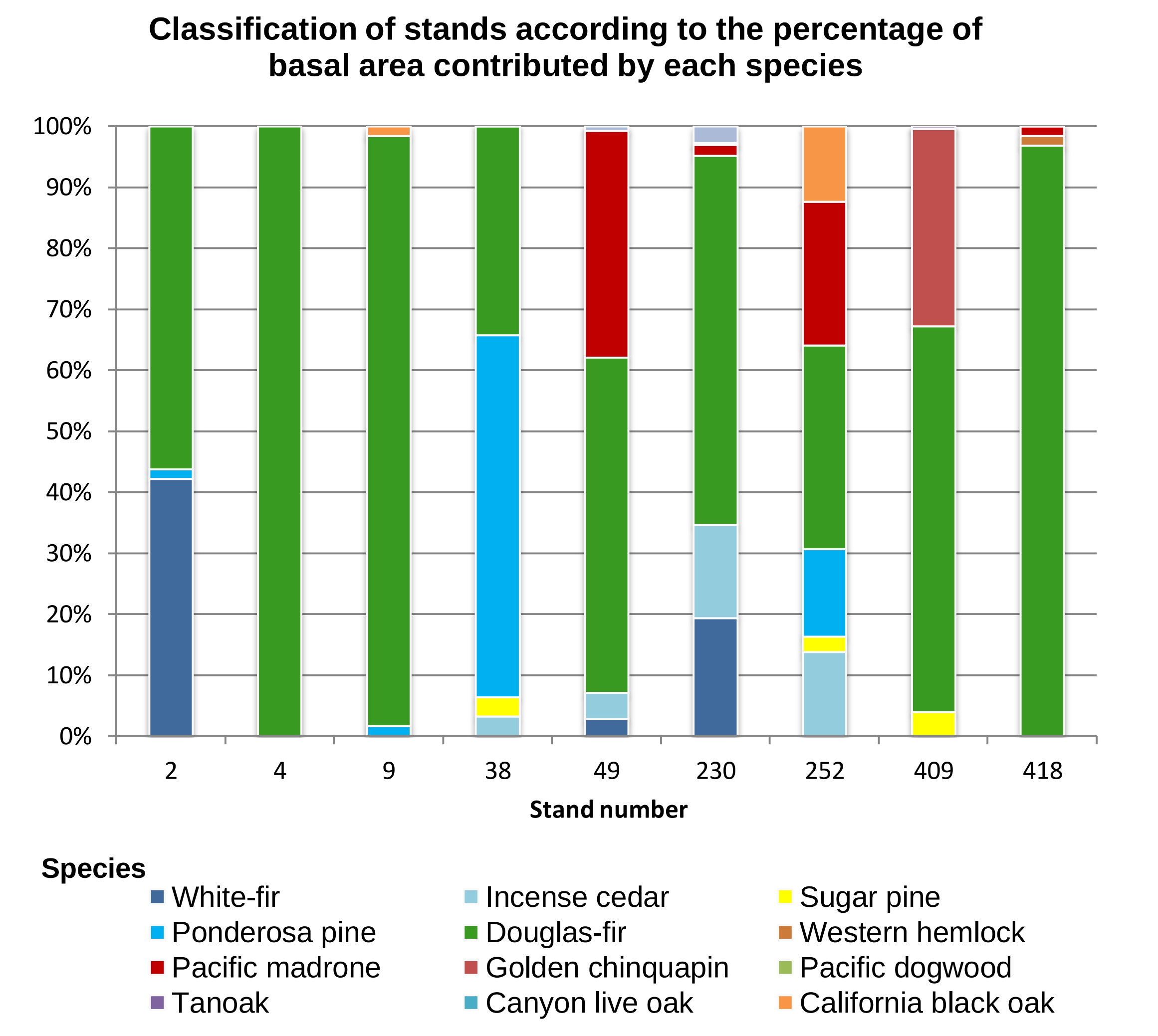


Figure 6. Example of classification of stands according to the percentage of basal area contributed by each species.

3.4. Main species data analysis

3.4.1. Douglas-fir (*Pseudotsuga menziesii)*

Douglas-fir (*Pseudotsuga menziesii*), also called also called red-fir, Oregon-pine, and Douglas-spruce, is the most important conifer in the Oregon because of its ecological significance (it has considerable morphological plasticity and is a major component of most forests of western North America), as well as its economic significance (it is one of the world's most important and valuable timber trees).

The Douglas-fir dataset compiled from the study stands consists of 5739 trees in pure Douglas-fir stands, 4109 trees in Mixed-conifer stands, and 2199 trees in Mixed-hardwood stands. Not all of these trees were measured for 5-year diameter growth because some were impossible to core, especially those with a diameter at breast height smaller than 7.62 cm. Table 6 (Section 4.1) indicates the Douglas-fir trees with a measurement of 5-year diameter growth.

Table 2 summarizes the main attributes of Douglas-fir trees in each type of stand. Trees 0.4 to 175 cm in diameter and 1.4 to 60 meters or more in height are present in the study plots.

Table 2. Summary of Douglas-fir attributes in each type of stand in the southwestern Oregon mixed-species plots.

Douglas-fir		**DBH(cm)**			**HT(m)**		
Type of Stand	**# trees**	**mean**	**sd**	**range**	**mean**	**sd**	**range**
Pure Stands Douglas-fir	5739	35.0	21.7	0.3-166.6	25.3	12.1	1.4-63.7
Mixed-Conifer stands	4109	29.3	22.27	0.3-177.2	20.7	12.1	1.4-61.6
Mixed-hardwood stands	2199	20.7	19.3	0.3-163.5	14.9	10.5	1.4-52.7

Height-diameter curves were fitted to the Douglas-fir trees in each type of stand to depict any systematic differences in height to diameter ratio. The model form was as follows:

[1] $$H = 1.37 + \beta_1 * \exp\left(\beta_2 / _{DBH} \right)$$

where

H = total height of the tree at the start of the growth period, m.

DBH = diameter at breast height at the start of the growth period, cm.

β_1 *and* β_2 = Parameters to be estimated from the data for each type of plot.

Table 3 shows the parameter estimates of β_1 and β_2 for each type of stand, and Figure 7 illustrates the resulting height-diameter curves for Douglas-fir in each of the three stand types: pure Douglas-fir stands, mixed-conifer stands, and mixed-hardwood stands.

Table 3. Parameters estimates in Douglas-fir Height-diameter curves.

Type of Stand	β_1	β_2
Pure Stands Douglas-fir	52.84	-22.77
Mixed-Conifer stands	49.07	-21.91
Mixed-hardwood stands	40.17	-17.68

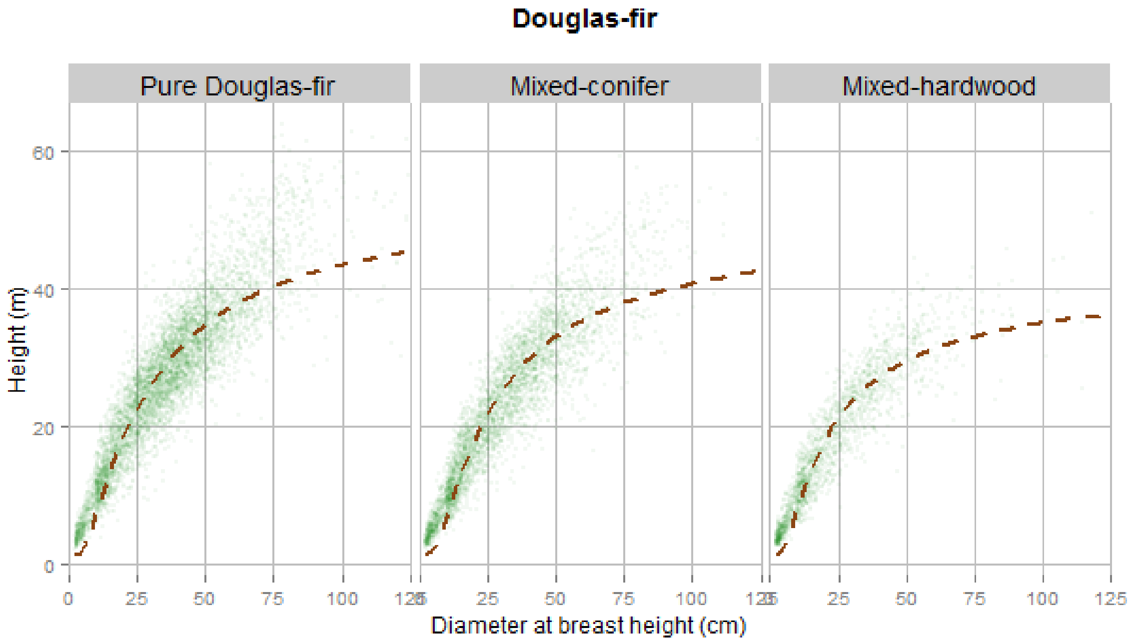


Figure 7. Height-diameter curves of Douglas-fir**.**

In southwestern Oregon, Douglas-fir is a widespread climax dominant or codominant. It is more shade tolerant than ponderosa pine, sugar pine, incense cedar, and noble fir (*Abies procera*) but less shade tolerant than white fir (Minore, 1979).

Old individuals typically have a narrow, cylindric crown beginning 20 to 40 meters above branch-free bole. Young, open-grown trees typically have branches near the ground. (Franklin, Cromack, & Denison, Ecological characteristics of old-growth Douglas-fir, 1981).

Foliage consists of yellowish-green, 2.5 cm long needles spirally arranged around the branchlets. This tree's rooting habit is not particularly deep. The roots of young coast

Douglas-fir tend to be shallower than roots of the same aged ponderosa pine, sugar pine, or incense-cedar (Minore, 1979).

3.4.2. Main competitive species

The dataset was subsetted to select the main competitive species (two conifers and two hardwoods) with a sufficient numbers of observations in the stands for the analysis. The selected competitor species were:

Conifers:
1) White/Grand fir (*Abies concolor* x *Abies grandis*);
2) Ponderosa pine (*Pinus Ponderosa)*;

Hardwoods:
3) Golden chinquapin (*Chrysolepis chrysophylla*);
4) Pacific madrone (*Arbutus menziesii*).

Table 4 shows the main attributes of each competitor species.

Table 4. Summary of the attributes of the main competitive species of the dataset.

SPECIES			DBH (cm)			HT (m)		
Name	**code**	**n**	**mean**	**sd**	**range**	**mean**	**sd**	**range**
White/Grand fir	*15*	1857	*27.7*	20.7	0.3-126.9	20.1	13.0	1.4-56.7
Ponderosa pine	*122*	841	*37.2*	23.4	0.3-127.7	23.2	11.9	1.4-58.0
Golden chinquapin	*361*	858	*18.8*	13.9	0.3-113.0	11.8	6. 8	1.4-31.1
Pacific madrone	*431*	810	*8.1*	8.9	0.3-67.1	6.0	5.3	1.4-25.7

Figures 8 and 9 illustrate the height-diameter curves of each competitor species in the different stand types. Equation [1] was fitted to the data for each competitor in each stand type, and the resulting estimates for parameters β_(1) and β_2 are showed in table 5.

Table 5. Parameters estimates for Main competitive species.

SPECIES	PARAMETERS	TYPE OF STAND	
Conifers		**Pure Douglas-fir**	**Mixed-conifer**
White/Grand fir (*Abies concolor* x *Abies grandis*)	β_1	49.50	53.88
	β_2	-20.21	-24.36

Ponderosa pine (*Pinus Ponderosa)*	β_1	55.33	50.95
	β_2	-29.22	-25.88
Hardwoods		**Pure Douglas-fir**	**Mixed-hardwood**
Golden chinquapin (Chrysolepis chrysophylla)	β_1	26.21	25.11
	β_2	-14.12	-14.98
Pacific madrone (*Arbutus menziesii*)	β_1	26.31	23.28
	β_2	-12.64	-12.08

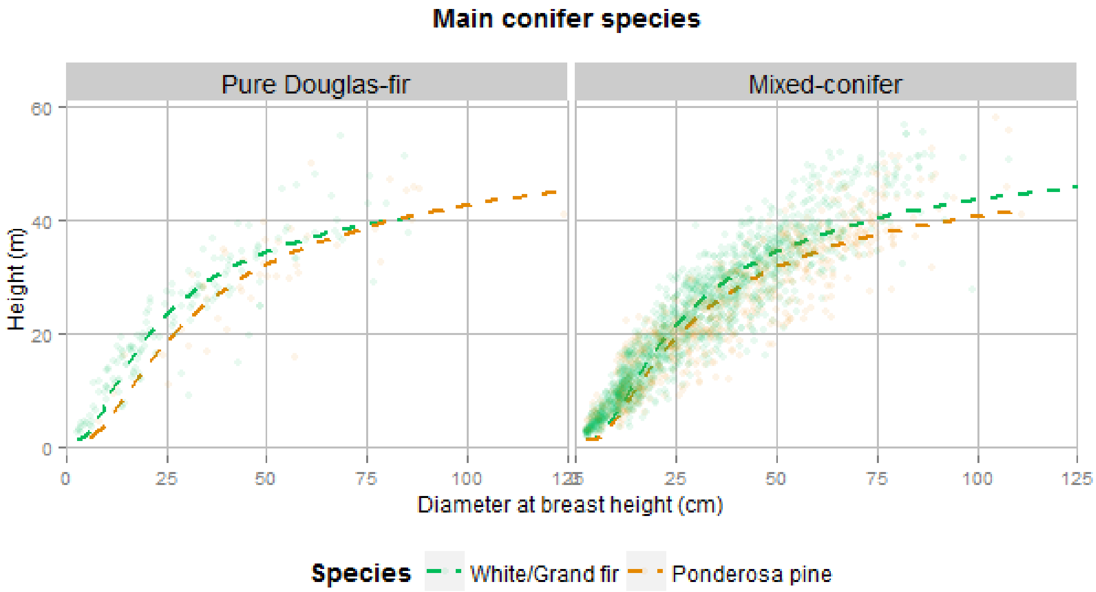


Figure 8. Height-diameter curves of main coniferous competitors to Douglas-fir.

White-fir diameters range from 0.3 to 126 cm, and height form 1.4 to 56 meters. Ponderosa pine diameters range from 0.3 to 127 cm and height from 1.4 to 58 meters.

White-fir is thought to be a slow growing species compare to Douglas-fir. Once established, white fir grows best in full sun. Shade-tolerant white fir saplings can, however, endure decades of suppression under a closed canopy or in dense brushfields. The growth is very slow under these conditions, and suppressed plants may be only 0.9 m tall at 50 years (Emmingham, 1972).

Ponderosa pine is shade intolerant and grows most rapidly in near full sunlight (Franklin & Dyrness, Natural vegetation of Oregon and Washington, 1973), but at higher elevation stands, is seral to trees that are more shade tolerant and moisture demanding. This generally includes Douglas-fir and White-fir. The crown of Ponderosa pine is conical and composed of stout branches (Cooper, 1960).

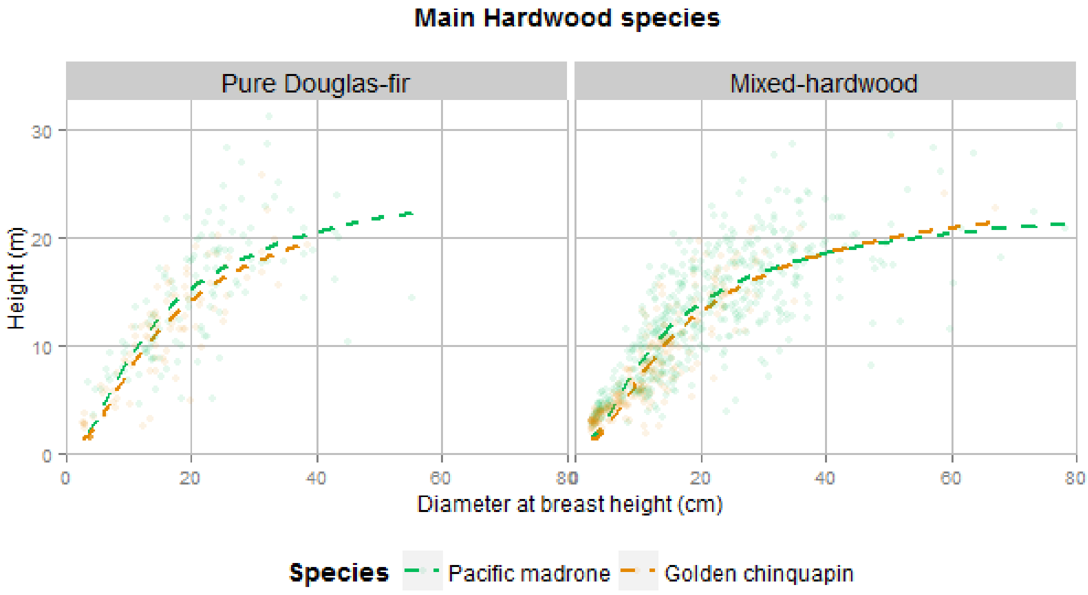


Figure 9. Height-diameter curves of main hardwood competitors to Douglas-fir.

Pacific madrone diameters range from 0.3 to 67 cm, and height form 1.4 to 31 meters. Ponderosa pine diameters range from 0.3 to 113 cm and height from 1.4 to 25 meters.

Pacific madrone trees have a single or multiple curved trunks support a broad spreading crown composed of heavy, irregularly-shaped limbs. A review indicates that Pacific madrone is a major component of Douglas-fir - tanoak -Pacific madrone forests. These forests are characterized by an overstory of Douglas-fir with tanoak and Pacific madrone sharing the secondary canopy in varying proportions (McDonald & Tappeiner, 1990). Pacific madrone has moderate to low shade tolerance and is considered an early-successional hardwood after timber harvest, fire, and other disturbances (Baker, 1949). In Appendix II, it is shown pictures of a typical Douglas-fir - Pacific madrone stand.

Golden chinquapin can either be a subdominant tree or a dominant understory shrub, depending upon conditions like moisture, elevation and overstory density. In the study area Golden chinquapin is most common in the midstory under conifers, although it occasionally occurs in the overstory. It has been categorized as intermediate shade tolerance, although the shrub form has been characterized as more shade-tolerant than the tree form and the tree form may be more common in open than in shaded conditions (McKee, 1990).

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1. Diameter growth of Douglas-fir by stand type

A test was made of the null hypothesis (H_0) of no significant difference between the 5-year diameter growth of Douglas-fir in pure Douglas-fir stands and mixed-species stands. The average diameter growth of Douglas-fir in each stand type is shown in table 6 and figures 10 and 11.

Table 6. Summary of five-year diameter growth of Douglas-fir.

DIAMETER GROWTH (cm)					
Type of Stand	**n**	**mean**	**median**	**sd**	**range**
Pure Stands Douglas-fir	5179	2.152	1.914	1.408	0.144 - 8.413
Mixed-Conifer	3425	2.233	2.046	1.450	0.144 - 8.902
Mixed-hardwood	1515	2.271	2.024	1.560	0.144 - 8.465

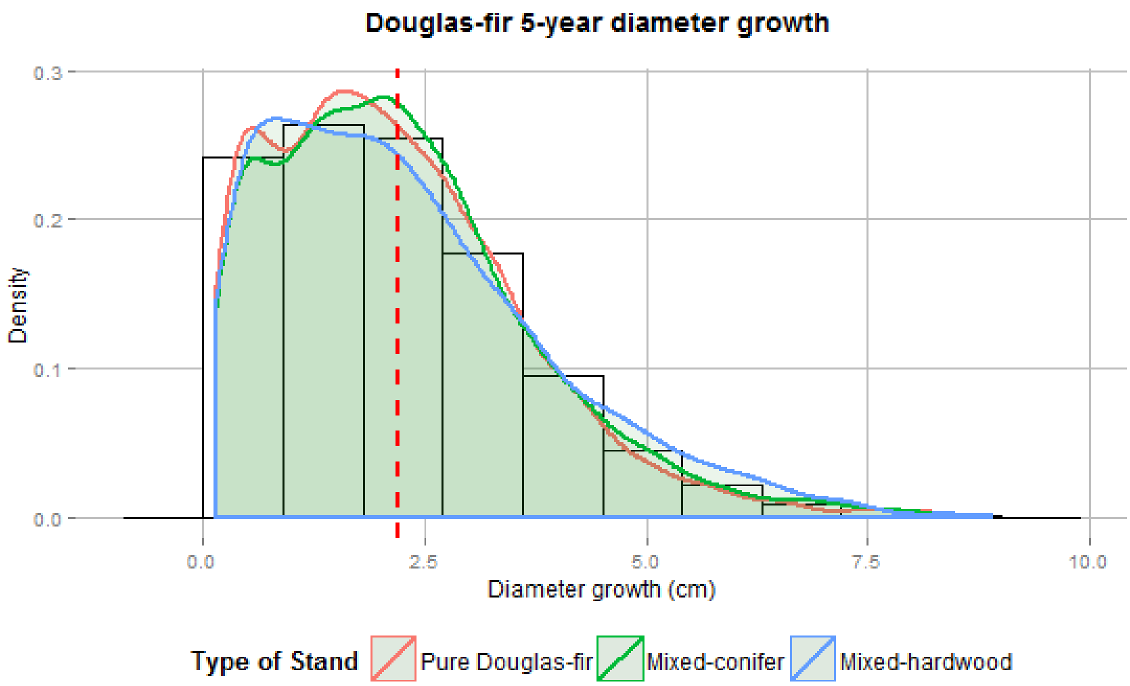


Figure 10. Histogram of Douglas-fir´s 5-year diameter growth (cm).
The mean of the population is represented with the Red line.

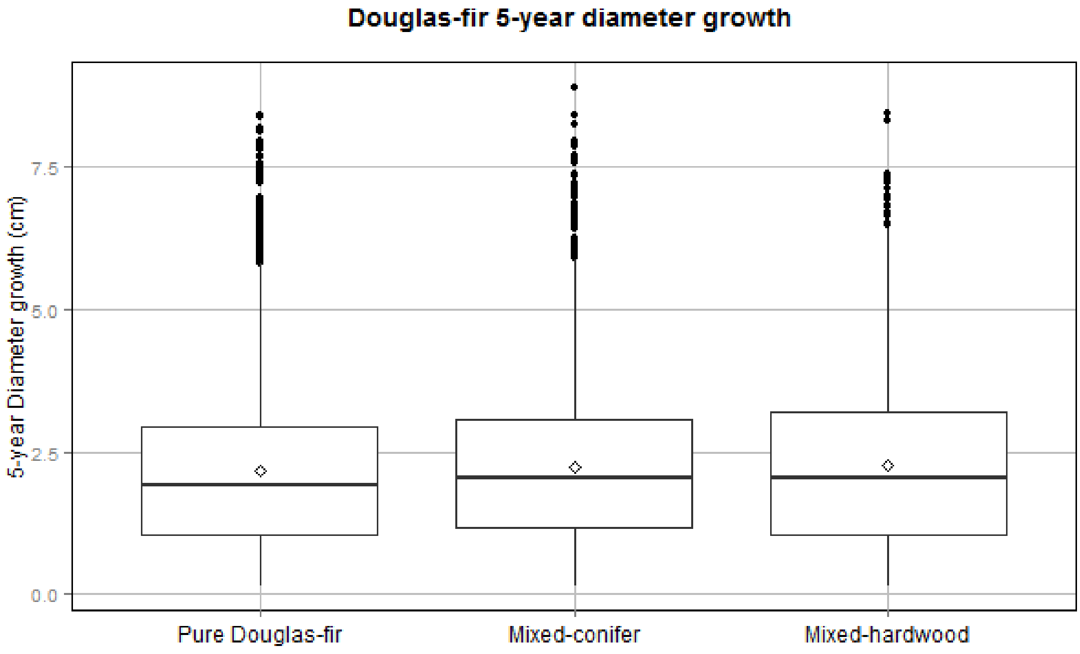


Figure 11. Boxplot of 5-year diameter growth of Douglas-fir (cm).

The Mann-Whitney-Wilcoxon test is a nonparametric method to test the null hypothesis that two samples come from the same population against the alternative hypothesis that they do not come from the same population.

In this case the statistic tests if the 5-year diameter growth of Douglas-fir in pure stands of Douglas-fir and in mixed-species stands comes from the same population, or if one stand type tends to have greater diameter growth. At a significance level of α=0.05, the analysis concluded that the 5-year diameter growth of Douglas-fir within pure and mixed-species stands are significantly different (p-value= 0.0459).

This test demonstrates that there are significant differences in diameter growth between mixed-species stands and pure Douglas-fir stands, with the caveat that none of the diameter growth rates were corrected for tree, stand, or site covariates that would cause the growth of each tree to respond positively or negatively.

4.2. Diameter growth rate

4.2.1. Original ORGANON equation

The basic equation used for predicting the diameter growth of Douglas-fir (and other species) in ORGANON was given by Hann and Larsen (1990) as:

$$\Delta D = e^{a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_4 X_4 + a_5 X_5 + a_6 X_6}$$

where

$X_1 = \ln(D + 2.54)$

$X_2 = D^2$

$X_3 = \ln(SI - 1.37)$

$X_4 = \frac{CR + 0.2}{1.2}$

$X_5 = COMA =$ Measure of the effect of one-sided competition

$X_6 = COMAB$ = Measure of the effect of two-sided competition

and

ΔD = future 5-year diameter growth rate, cm.

D = diameter at breast height at the start of the growth period, cm.

CR = crown ratio at the start of the growth period.

SI = Hann and Scrivani (1987) definition of Douglas-fir site index, m.

COMA =measure of the effect of one-side competition (from above).

COMAB = measure of the effect of two-side competition (from above and below).

In the initial step of the analysis, the variables COMA and COMAB representing competitive effects took the following form:

$COMA_0 = \frac{BAL^2}{\ln(D+12.7)}$

$COMAB_0 = BA_i^{0.5}$

4.2.2. Foliage mass variable

Because the two competition variables above imply that a unit of basal area imposes the same degree of competition regardless of the species, a possible improvement was explored under the assumption that species varied in the ratio of foliage mass to basal area.

In this case, species with a higher amount of foliage per unit basal area should have a stronger competitive effect on Douglas-fir, all else being equal. Therefore, the competition variables were modified by replacing basal area with tree foliage mass, as follows:

$$COMA_1 = \frac{F^2}{(\ln(D + 12.7))}$$

$$COMAB_1 = Fs_i^{0.5}$$

where *F* is the predicted foliage mass of trees larger than the subject tree and *Fs* is the predicted total foliage mass on the subplot, with foliage mass of individual trees estimated from the non-linear equations developed by Jenkins et al. (2004).

For calculating foliage weight in the system presented by Jenkins et al. (2004), total biomass of the tree is predicted first with the following equation form:

[3] $$Bm = Exp(\beta_0 + \beta_1 \times \ln DBH)$$

where *Bm* is the total aboveground biomass (kg) of the tree; *DBH* is the diameter at breast height; and β_0 and β_1 are parameters that depend of the subject species. Table 7 shows the estimates of these two parameters published for each species by Jenkins et al. (2004).

Table 7. Parameters for estimating total aboveground biomass for various forest tree species (from Jenkins et al. 2004)

SPECIES		***SPECIES GROUP***		***PARAMETERS***	
code	***name***	***code***	***name***	β_0	β_1
351	Red alder	aa	aspen/alder/ cottonwood/ willow	-2.2094	2.3867
352	White alder				
920	Willow				
41	Port-Orford cedar	cl	cedar/larch	-2.0336	2.2592
81	Incense cedar				
242	Northern white-cedar				

202	Douglas-fir	df	Douglas-fir	-2.2304	2.4435
312	Bigleaf maple	mb	soft maple/ birch	-1.9123	2.3651
361	Pacific madrone	mh	mixed hardwood	-2.48	2.4835
431	Golden chinquapin				
492	Pacific dogwood				
631	Tanoak				
760	Cherry, plum spp.				
999	All others hardwoods				
805	Canyon live oak	mo	hard maple/ oak/ hickory/ beech	-2.0127	2.4342
815	Oregon white oak				
818	California black oak				
103	Knobcone pine	pi	pine	-2.5356	2.4349
116	Jeffrey pine				
117	Sugar pine				
119	Western white pine				
122	Ponderosa pine				
15	White fir/Grand fir	tf	true fir/ hemlock	-2.5384	2.4814
19	Subalpine fir				
231	Pacific yew				
263	Western Hemlock				

After estimating total aboveground biomass, the proportion of that biomass in foliage was estimated by the following equation:

[4] $$ratio(Fo) = exp\left(\alpha_0 + \frac{\alpha_1}{DBH}\right)$$

where *Fo* is the predicted foliage weight (kg) and α_0 and α_1 are parameters whose estimates are presented by Jenkins (2004) and shown in Table 8. Total foliage biomass, *Fo*, was estimated as the product of *Bm* and ratio (*Fo*).

Table 8. Parameter estimates for $\boldsymbol{\alpha_0}$ and $\boldsymbol{\alpha_1}$ from Jenkins et al. (2004)

SPECIES GROUP		***PARAMETERS***	
code	***name***	$\boldsymbol{\alpha_0}$	$\boldsymbol{\alpha_1}$
hw	Hardwood	-4.0813	5.8816
co	Softwood	-2.9584	4.4766

The foliage weight per unit area of each stand (T/ha) was calculated from the sum of the estimated foliage weight of individuals trees multiplied by their expansion factor.

The total foliage weight per point in each stand type is shown in Table 9. This variable, that measures the quantity of foliage, is directly related to the amount of precipitation and solar radiation reaching the forest floor as well as penetration of light through the crowns.

Table 9. Summary of foliage weight per ha at sample points in each type of stand.

FOLIAGE WEIGHT PER POINT (T/ha)				
Type of Stand	**mean**	**median**	**sd**	**range**
Pure Stands Douglas-fir	19.31	18.75	8.32	0.187 - 50.4
Mixed-conifer	15.55	15.17	7.97	0.188 - 51.5
Mixed-hardwood	10.74	10.39	6.20	0.088 - 32.7

In figure 12, the expected relationship between foliage mass of the stand and diameter growth of Douglas-fir is illustrated.

4.2.3. Foliage mass equations

The following five equations forms were fit to the total dataset for Douglas-fir, including trees on pure Douglas-fir, mixed-conifer and mixed-hardwood stands:

EQUATION D1: *REDUCED (BASE)*

$$ln(\Delta D) = a_0 + a_1 \times \ln(D + 2.54) + a_2 \times D^2 + a_3 \times \ln(SI - 1.37) + a_4 \times \left(\frac{CR + 0.2}{1.2}\right)$$

EQUATION D2: *BASE* + *COMA₀* + *COMAB₀*

$$ln(\Delta D) = a_0 + a_1 \times \ln(D + 2.54) + a_2 \times D^2 + a_3 \times \ln(SI - 1.37) + a_4 \times \left(\frac{CR + 0.2}{1.2}\right)$$

$$+a_5 \times \left(\frac{BAL_i^2}{\ln(D + 12.7)}\right) \qquad \rightarrow COMA_0$$

$$+a_6 \times \left(BA_i^{0.5}\right) \qquad \rightarrow COMAB_0$$

EQUATION D3: *BASE* + *COMA₀* + *COMAB₁*

$$ln(\Delta D) = a_0 + a_1 \times \ln(D + 2.54) + a_2 \times D^2 + a_3 \times \ln(SI - 1.37) + a_4 \times \left(\frac{CR + 0.2}{1.2}\right)$$

$$+a_5 \times \left(\frac{BAL_i^2}{\ln(D + 12.7)}\right) \qquad \rightarrow COMA_0$$

$$+a_6 \times Fs^{0.5} \qquad \rightarrow COMAB_1$$

EQUATION D4: *BASE* + *COMA₁* + *COMAB₀*

$$ln(\Delta D) = a_0 + a_1 \times \ln(D + 2.54) + a_2 \times D^2 + a_3 \times \ln(SI - 1.37) + a_4 \times \left(\frac{CR + 0.2}{1.2}\right)$$

$$+a_5 \times \left(\frac{F^2}{(\ln(D + 12.7))}\right) \qquad \rightarrow COMA_1$$

$$+a_6 \times \left(BA_i^{0.5}\right) \qquad \rightarrow COMAB_0$$

EQUATION D5: *BASE* + *COMA₁* + *COMAB₁*

$$ln(\Delta D) = a_0 + a_1 \times \ln(D + 2.54) + a_2 \times D^2 + a_3 \times \ln(SI - 1.37) + a_4 \times \left(\frac{CR + 0.2}{1.2}\right)$$

$$+a_5 \times \left(\frac{F^2}{(\ln(D + 12.7))}\right) \qquad \rightarrow COMA_1$$

$$+a_6 \times Fs^{0.5} \qquad \rightarrow COMAB_1$$

The equation [D1], called the Reduced or Base model, is the one without competition predictors. This equation will be used to assess the gains achieved by adding the alternative variables for representing competition.

Equations [D2] to [D5] then used different combinations of the competition predictors ($COMA_0$, $COMAB_0$, $COMA_1$ and $COMAB_1$).

The fit of equations [D2] to [D5] was evaluated by taking the mean square error (MSE) for each equation and dividing it by the MSE for the Reduced (Base) equation, and expressing the quotient as a percentage (Biging G.S. & Dobbertin, M., 1995; Bravo, Hann, & Maguire, 2001.).

Table 10 presents the parameter estimates for each equation. All the parameter estimates were significantly different from zero (at a significance level of α=0.001). The size and signs of the parameter estimates were as expected to produce the expect diameter growth pattern of a forest-grown tree.

Table 10. Parameter estimates for equations [D1] through [D5].

Variable	Parameter	Eq 1	Eq 2	Eq 3	Eq 4	Eq 5
Constant	a_0	-3.619***	-3.440***	-3.597***	-3.805***	-3.934***
$X_1 = ln(D + 2.54)$	a_1	0.735***	0.551***	0.644***	0.799***	0.777***
$X_2 = D^2$	a_2	$-9.1 x10^{-5}$***	$-9.1 x10^{-5}$***	$-8.9 x10^{-5}$***	$-1.0 x10^{-4}$***	$-9.4 x10^{-5}$***
$X_3 = ln\ (SI - 1.37)$	a_3	0.847***	1.028***	1.040***	1.006***	0.989***
$X_4 = ln\left(\frac{CR+0.2}{1.2}\right)$	a_4	1.843***	1.257***	1.164***	1.298***	1.362***
$COMA_0 = \frac{BAL^2}{ln(D+12.7)}$	a_5	-	-0.007***	-0.006***	-	-
$COMAB_0 = BA^{0.5}$	a_6	-	-0.061***	-	-0.178***	-
$COMA_1 = \frac{F^2}{ln(d+12.7)}$	a_5	-	-	-	$-0.003x10^{-6}$***	$-0.003x10^{-6}$***
$COMAB_1 = Fs^{0.5}$	a_6	-	-	-0.004***	-	-0.004***

Adjusted R-squared (Adj. R^2), mean square error (MSE), the reduction in MSE in percentage (∆MSE%) and residual standard error for equations [D1] to [D5] are presented in Table 11.

In all the equations, the inclusion of competition variables reduced the MSE by more than 13% over the reduced equation.

Equation [D3] with BAL as one-sided competition and Fs as two-sided competition seemed to be the best, with a reduction in MSE of 18%.

The use of the variable F to measure the foliage of trees larger than the subject tree does not perform well in equations [D4] and [D5], with less reduction of MSE than equations [D2] and [D3].

BAL seems to be the best variable to characterize one-sided completion and Fs to characterize two-sided competition.

Table 11. Diameter growth statistics used to evaluate the fit of each equation.

Nº	DESCRIPTION	Adj. R^2	MSE	∆MSE%	Residual Std. Error
EQ 0	*REDUCED (BASE)*	0.474	0.3629	100.00%	0.603 (df = 10114)
EQ 1	$BASE + COMA_0 + COMAB_0$	0.559	0.3047	83.97%	0.552 (df = 10112)
EQ 2	$BASE + COMA_0 + COMAB_1$	0.569	0.2976	82.00%	0.546 (df = 10112)
EQ 3	$BASE + COMA_1 + COMAB_0$	0.555	0.3074	84.70%	0.555 (df = 10112)
EQ 4	$BASE + COMA_1 + COMAB_1$	0.548	0.3123	86.05%	0.559 (df = 10112)

To provide more insight about the influence of sample point foliage mass per ha on 5-year diameter growth of Douglas-fir, the relationship between these two variables was plotted for each stand type. In addition, the Douglas-fir trees were grouped into diameter classes to reveal how this variable (F) influences the diameter growth of specific tree sizes.

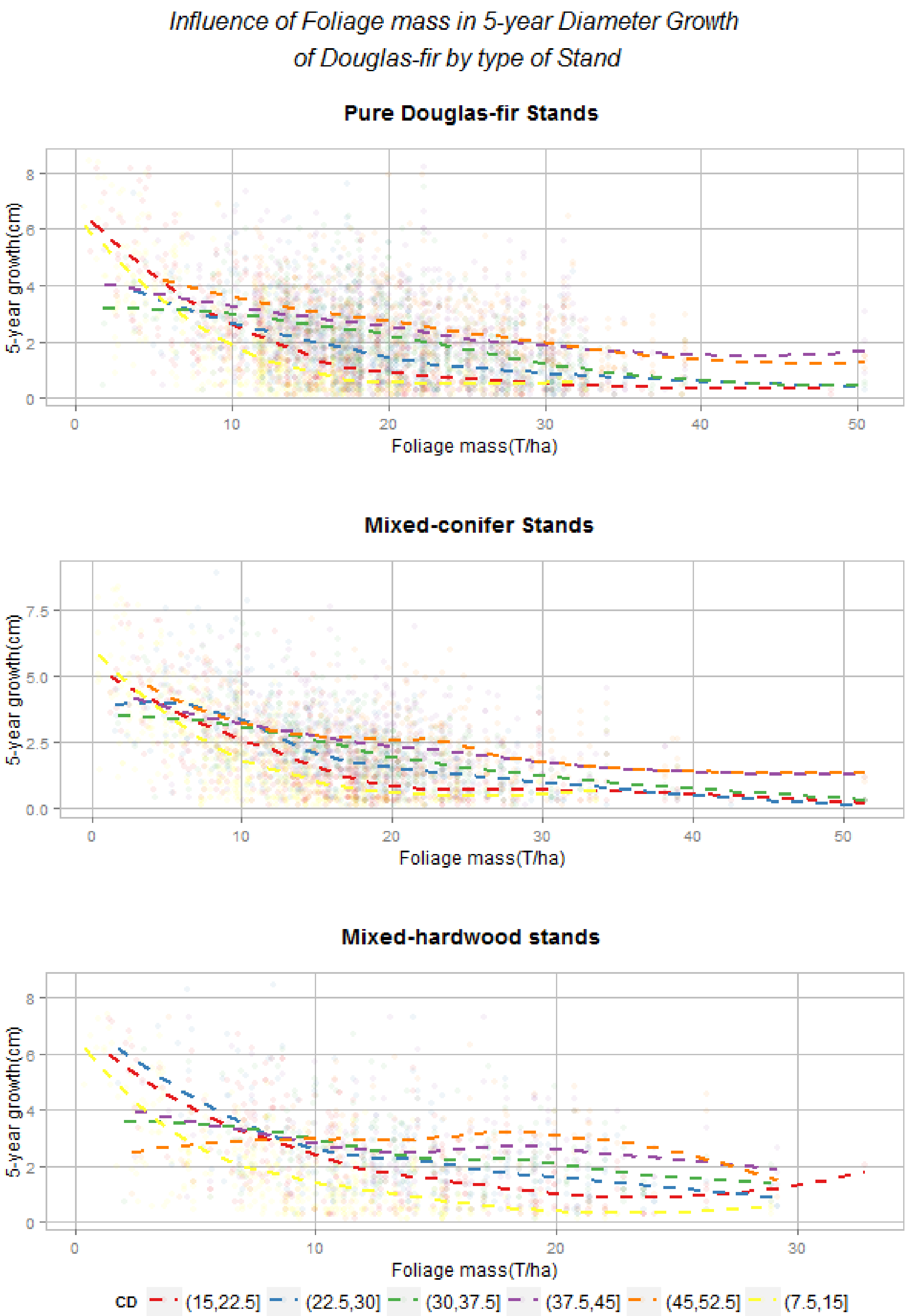


Figure 12. Influence of foliage weight per ha at each sample point on 5-year diameter growth of Douglas-fir in pure Douglas-fir stands, mixed-conifer stands and mixed-hardwood stands by diameter class (CD).

Figure 12 shows that increasing total foliage mass has a more negative effect on small trees than on large trees. This trend probably indicates increasing competition from above for small trees and increasing competition from below for larger trees. The influence of the foliage mass is not so different between the types of stands.

Another unexpected result was that the variable of foliage mass outperforms basal area for two-sided competition, suggesting that species do in fact differ in the amount of competition they impose for a given unit of basal area.

This result makes the case for using variables that more accurately reflect the attributes of the species that would indicate expected intensity of competition.

CONCLUSIONS

5. CONCLUSIONS

1. There is a significant difference between the diameter growth of Douglas-fir in pure Douglas-fir stands and in mixed-species stands.

2. Competition variables are important for predicting individual-tree diameter growth in mixed-species stands.

3. Foliage weight is an important variable representing two-sided competition effects on diameter growth of Douglas-fir in mixed-species forests.

ACKNOWLEDGMENTS

6. ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor Doug Maguire who was abundantly helpful and offered invaluable assistance, support and guidance.

Deepest gratitude is also due to the members of Maguire staff, Doug Mainwaring, Eladio Cornejo, Henry Rodman, Sukhyun Joo, Ramiro Oliveri, André Faria and Derek Gourley without whose knowledge and assistance this study would not have been successful.

Thanks to University of Valladolid and Felipe Bravo for giving me the opportunity of this awesome experience.

Special thanks to all my family and friends who always been there.

LITERATURE CITED

7. LITERATURE CITED

Baker, F. S. (1949). *A revised tolerance table. .* Journal of Forestry.

Bielak, K., Dudzinska, M., & Pretzsch, H. (2014). Mixed stands of Scots pine (Pinus sylvestris L.) and Norway spruce [Picea abies (L.) Karst] can be more productive than monocultures. Evidence from over 100 years of observation of long-term experiments. *Forest Systems*, v. 23, n. 3, p. 573-589.

Biging G.S., & Dobbertin, M. (1995). *Evaluation of Competition Indices in Individual Tree Growth Models.* Forest Science.

Bravo, Hann, & Maguire. (2001.). Impact of competitor species composition on predicting diameter growth and survival rates of Douglas-fir trees in southwestern Oregon. *Canadian Journal of Forest Research*, 31:2237-2247.

Bravo-Oviedo, A. P. (2014). European Mixed Forests: definition and research perspectives. *Forest systems*, 23(3), 518-533.

Cooper, C. F. (1960). *Changes in vegetation, structure, and growth of Southwestern pine forests since white settlement.* Ecological Monographs, 30: 129–164. .

Emmingham, W. H. (1972). *Conifer growth and plant distribution under different light environments in the Siskiyou Mountains of southwestern Oregon.* Corvallis, OR: Oregon State University,Thesis.

FAO. (2000). *Evaluación de los recursos forestales mundiales 2000.* ORGANIZACIÓN DE LAS NACIONES UNIDAS PARA LA AGRICULTURA Y LA ALIMENTACIÓN.

Franklin, J. F., & Dyrness, C. T. (1973). *Natural vegetation of Oregon and Washington.* Portland, OR: U.S. Department of Agriculture, Forest Service.

Franklin, J. F., Cromack, K. J., & Denison, W. (1981). *Ecological characteristics of old-growth Douglas-fir.* Portland, OR: Department of Agriculture, Forest Service.

Hann, D. (2011). *ORGANON User´s Manual Edition 9.1.* Corvallis, OR: Department of Forest Engineering, Resources and Management.

Hann, D. W. (1983). *Field procedures for measurement of standing trees.* Corvallis, Or: Department of Forest Management.

Hann, D.W. and Larsen, D.R. (1990). *Diameter growth equations for fourteen tree species in Southwest Oregon.* Corvallis, OR: Forest Research Laboratory, Oregon State University.

Hobbs, S. D. (1992). *Reforstation Practices in Southwestern Oregon and Northern California.* Corvallis,Or: Forest Research Laboratory,Oregon State University.

Jenkins J.C., C. D. (2004). *Comprehensive Database of Diameter-Based Biomass Regressions for North American Tree Species.* Comprehensive Database of Diameter-Based Biomass Regressions for North American Tree Species. General Technical Report.

McDonald, P. M., & Tappeiner, J. C. (1990). *Arbutus menziesii Pursh Pacific madrone.* Washington, DC: U.S. Department of Agriculture, Forest Service.

McKee, A. (1990). *Castanopsis chrysophylla (Dougl.) A. DC. giant chinkapin.* Washington, DC: Silvics of North America. Vol. 2. Hardwoods. Agric. Handb. 654.

Minore, D. (1979). *Comparative autecological characteristics of northwestern tree species.* Portland, OR: Department of Agriculture , Forest Service.

Oregon Forest Resources Institute. (2015-2016). *Oregon Forest Facts & Figures.*

Wagner, D. (1997). Klamath-Siskiyou region, California and Oregon, U.S.A. En *Centres of Plant Diversity, the Americas, 3* (págs. 74-76).

Whittaker, R. H. (1960). “Vegetation of the Siskiyou Mountains, Oregon and California”. Ecological Monographs 30.3.

APPENDICES

8. APPENDICES

APPENDIX I. EXAMPLES OF STATISTICS MODELS WITH R

Packages used in this study

```
library(dplyr)
library(ggplot2)
library(grid)
library(gridExtra)
library(stargazer)
library(plyr)
library (car)
library (relaimpo)
library (MASS)
```

Missing values

```
dataplots[dataplots==-99]<-NA
```

Classification of stands according to the percentage of basal area contributed by each species

```
Tabla1$SPP <- as.numeric(as.character(Tabla1$SPP))
Tabla2 <- split(Tabla1, Tabla1$PLOT)

plot.table <- do.call(rbind,lapply(Tabla2,function(x){

  DF = x[x$SPP == 202, ] #ouglas-fir  species code
  CO = x[x$SPP < 300 & x$SPP != 202,] #Coniferous species code
  HW = x[x$SPP > 300,]          #Harwood species code

  ba.pct.df = sum(DF$BAper, na.rm = TRUE)
  ba.pct.co = sum(CO$BAper, na.rm = TRUE)
  ba.pct.hw = sum(HW$BAper, na.rm = TRUE)

  type = ifelse(ba.pct.df > 80, 1,
           ifelse(ba.pct.co > 80 | ba.pct.hw >80 , 2,
                ifelse(ba.pct.co > ba.pct.hw,3,
                     ifelse(ba.pct.hw > ba.pct.co,4,5))))

  out = data.frame(PLOT = (x$PLOT),type, ba.pct.df, ba.pct.co, ba.pct.hw)
  return(out)}))

plot.table$type <- as.factor(plot.table$type)
summary(plot.table$type)

Tabla1$type <- plot.table$type
```

Calculate of basal area of trees with larger diameter than the subject one (BAL)

```
dataplots$BAL <- unlist(
  by(dataplots, dataplots$PLOT, function(y)    # by PLOT
    sapply(y$DBHS, FUN = function(x)            #for each diameter
      sum(y[x < y$DBHS, ]$BAm2ha ))))           #sum applicable basal area
```

 # Example of Height ~ Diameter curves.

Douglas-fir HTS~DBHS (nls)
Use function filter (dplyr package) to create the data for each specie

```
data1 <- filter(dataplots10,SPP=="202")
data2 <- filter(dataplots10,SPP=="122"| SPP=="15",TYPE != "4")
data3 <- filter(dataplots10,SPP=="361"| SPP=="431",TYPE != "3")
DFPure <- filter(data1,TYPE == "1")
DFMiCo <- filter(data1,TYPE == "3")
DFMiHw <- filter(data1,TYPE == "4")
```

Use function nls to determine the nonlinear least-squares estimates of the parameters of a nonlinear model.

```
 nlsDFPure <- nls(formula=HTS~1.3+a*exp(b/DBHS),data = DFPure,start=list(a=1,b=1))
nlsDFMiCo <- nls(formula=HTS~1.3+a*exp(b/DBHS),data = DFMiCo,start=list(a=1,b=1))
nlsDFMiHw <- nls(formula=HTS~1.3+a*exp(b/DBHS),data = DFMiHw,start=list(a=1,b=1))
```

Create a function to name the change the labels of the ggplot

```
data1$TYPE<- as.factor(data1$TYPE)
data1_names <- list(
          '1'="Pure Douglas-fir",
          '3'="Mixed-conifer",
          '4'="Mixed-hardwood")
data1_labeller <- function(variable,value){
  return(data1_names[value])
}
```

#ggplot

```
ggplot(data1,aes(x=DBHS,y=HTS))+geom_point(alpha=0.06,color="forestgreen",size=0.9)+
        facet_grid(~TYPE,labeller = data1_labeller)+
        geom_smooth(method="nls", formula=y~1.3+a*exp(b/x), se=FALSE,
                    start=list(a=1,b=1),linetype = "dashed",size = 1,color="chocolate4")+
         labs(title = "Douglas-fir \n ", x= "Diameter at breast height (cm)" ,y= "Height (m)")+
         coord_cartesian(xlim = c(0,125))+
         theme(plot.title =element_text(face = "bold",size = 14),
                     axis.title = element_text(size=12),
                    legend.position ="bottom",
                     legend.text=element_text(size=12),
                     panel.background = element_rect("white"),
                    panel.grid.major = element_line(colour = "grey"),
                    panel.grid.minor = element_blank(),
                    strip.text = element_text(size=14))
```

Main conifer HTS~DBHS (nls)

```
data2_names <- list(
  '1'="Pure Douglas-fir",
  '3'="Mixed-conifer")
data2_labeller <- function(variable,value){
  return(data1_names[value])
```

```
}

ggplot(data2,aes(x=DBHS,y=HTS,colour=SPP))+facet_grid(~TYPE,labeller = data2_labeller)+
    geom_smooth(method="nls", formula=y~1.3+a*exp(b/x),se=FALSE, start=list(a=-1,b=-
        1),linetype = "dashed",size = 1)+
    labs(title = "Main conifer species \n", x= "Diameter at breast height (cm)" ,y= "Height
        (m)",legend.title="Species")+
    theme(plot.title =element_text(face = "bold",size = 14),
        axis.title = element_text(size=12),
        legend.position ="bottom",
        legend.text=element_text(size=12),
        legend.title=element_text(size=14),
        panel.background = element_rect("white"),
        panel.grid.major = element_line(colour = "grey"),
        panel.grid.minor = element_blank(),
        strip.text = element_text(size=14))+
  geom_point(alpha=0.09)+
  scale_colour_discrete(h = c(55, 310) + 90, c = 100, l = 65,name="Species",breaks=c("15",
        "122"),labels=c("White/Grand fir", "Ponderosa pine"))
```

 # Histogram of Douglas-fir´s 5-year diameter growth (cm)

```
ggplot(dataDF, aes(x=DGRO,colour=factor(TYPE))) +
  geom_histogram(aes(y=..density..),  binwidth=0.9, colour="black", fill="white")+
  geom_density(alpha=.09, fill="forestgreen",size=0.8)+
  labs (title = "Douglas-fir 5-year diameter growth ",
        x= "Diameter growth (cm)" ,
        y= "Density",
        legend.title="Type of stand")+
  theme(plot.title =element_text(face = "bold",size = 14),
     axis.title = element_text(size=12),
     legend.position = "bottom",
     legend.text=element_text(size=12),
     panel.background = element_rect("white"),
     legend.title=element_text(size=13),
     panel.grid.major = element_line(colour = "grey"),
     panel.grid.minor = element_blank())+
  scale_colour_discrete(name="Type of Stand",breaks=c("1", "3", "4"),
     labels=c("Pure Douglas-fir", "Mixed-conifer", "Mixed-hardwood"))+
  geom_vline(aes(xintercept=mean(DGRO, na.rm=T)),   # Ignore NA values for mean
       color="red", linetype="dashed", size=0.9)
```

 # Boxplot of 5-year diameter growth of Douglas-fir.

```
ggplot(dataplots[dataplots$SPP=="202"&dataplots$DBHS>7.4,])+
    aes(x=TYPE,y=DGRO,na.rm=T)+
    geom_boxplot()+
    stat_summary(fun.y=mean, geom="point", shape=5, size=2)+
    scale_x_discrete(breaks=c("1", "3", "4"),labels=c("Pure stands DF", "Mixed-conifers", "Mixed-
        hardwood"))+
    theme_bw (base_family = "Times")+
    labs (title = "Diameter growth of Douglas-fir")
```

Wilcoxon Rank Sum and Signed Rank Tests

```
wilcox.test(dataDF_T1$DGRO,dataDF_T3$DGRO,paired = FALSE,var.equal = FALSE,conf.level =
0.90,na.action=na.exclude)

wilcox.test(dataDF_T1$DGRO,dataDF_T4$DGRO,paired = FALSE,var.equal = FALSE,conf.level =
0.90,na.action=na.exclude)

wilcox.test(dataDF_T3$DGRO,dataDF_T4$DGRO,paired = FALSE,var.equal = FALSE,conf.level =
0.90,na.action=na.exclude)

wilcox.test(dataDF_T1$DGRO,dataDF_T34$DGRO,paired = FALSE,var.equal = FALSE,conf.level =
0.95,na.action=na.exclude)
```

Fit the models

```
EQ0_ALL <- lm (log(DGRO) ~ log(DBHS+2.54)
        +I(DBHS^2)
        +log(DFSI-1.37)
        +log((CR+0.2)/1.2)
        ,na.action = na.exclude,
        data = dataModel)
mean(EQ0_ALL$residuals^2)

EQ1_ALL <- lm (log(DGRO) ~ log(DBHS+2.54)
        +I(DBHS^2)
        +log(DFSI-1.37)
        +log((CR+0.2)/1.2)
        +I((BAL^2)/(log(DBHS+12.7)))
        +I(BAtotal^0.5)
        ,na.action = na.exclude,
        data = dataModel)
summary(EQ1_ALL)

EQ2_ALL <- lm (log(DGRO) ~ log(DBHS+2.54)
        +I(DBHS^2)
        +log(DFSI-1.37)
        +log((CR+0.2)/1.2)
        +I((BAL^2)/(log(DBHS+12.7)))
        +I(((FPO_CONI+Fpo_202+FPO_HW))^0.5)

        ,na.action = na.exclude,
        data = dataModel)
mean(EQ2_ALL$residuals^2)

EQ3_ALL <- lm (log(DGRO) ~ log(DBHS+2.54)
        +I(DBHS^2)
        +log(DFSI-1.37)
        +log((CR+0.2)/1.2)
        #+I((BAL^2)/(log(DBHS+12.7)))
        +I(BAtotal^0.5)
        +I((FL_point^2)/(log(DBHS+12.7)))
        #+I(Fpo_202)
```

```
              ,na.action = na.exclude,
              data = dataModel)

mean(EQ3_ALL$residuals^2)

EQ4_ALL <- lm (log(DGRO) ~ log(DBHS+2.54)
              +I(DBHS^2)
              +log(DFSI-1.37)
              +log((CR+0.2)/1.2)
              +I((FL_point^2)/(log(DBHS+12.7)))
              +I((FPO_CONI+Fpo_202+FPO_HW)^0.5)
              ,na.action = na.exclude,
              data = dataModel)
summary(EQ4_ALL)
mean(EQ4_ALL$residuals^2)
```

Other functions to evaluate the models

```
# Function that calculates generalized variance-inflation factors generalized linear models
vif(EQ3_ALL)

# Function to calculate relative importance metrics
calc.relimp(EQ3_ALL)

# These functions construct component + residual plots
crPlots(EQ2_ALL)

# Custom function for summary & diagnostic output of fitted model
lm.model.diagnostics<-function(formula, dataset){

  #run model and print specific output
  model1<-lm(formula=formula, data=dataset)
  stats<-round(c(summary(model1)$fstatistic[c(1,3)],
                summary(model1)$sigma,
                summary(model1)$r.squared,
                summary(model1)$adj.r.squared),3)
  names(stats)<-c("F","DF", "Sigma","Rsq","AdjRsq")
  l1<-list(round(summary(model1)$coefficients,3), stats)
  names(l1)<-c("Coefficients","Stats")
  print(l1)

  #run specific diagnostic tests
  par(mfrow=c(1,3))
  hist(model1$residuals, main="Histogram of residuals", xlab="")
  plot(model1, 1)
  plot(model1, 2)
}
```

#Output fittng models

```
require(stargazer)
stargazer(EQ0_ALL,EQ1_ALL,EQ2_ALL,EQ3_ALL,EQ4_ALL,
        type="html",out = "EQ foliage por point.html")
```

 # GGPLOT: Figure 12. "Influence of foliage weight per ha at each sample point on 5-year diameter growth of Douglas-fir"

```
GT1 <- ggplot(dataModel[dataModel$TYPE==1,])+
          aes(x=(FPO_CONI+Fpo_202+FPO_HW)*0.001,y=DGRO,color=CD)+
         geom_point(alpha=0.08)+
         geom_smooth(method="loess",se=F,size=0.8,linetype="dashed")+
         labs(title = "Pure Douglas-fir Stands", x= expression(paste("Foliage mass(T/ha)")) ,y=
               "5-year                    growth(cm)")+
         scale_colour_brewer(palette = "Set1")
         theme(plot.title =element_text(face = "bold",size = 14),
               legend.position ="none",
               axis.title = element_text(size=12),
               legend.text=element_text(size=12),
         panel.background = element_rect(fill="white"),
               panel.grid.major = element_line(colour = "grey"),
               panel.grid.minor = element_blank(),
               axis.line = element_line(colour = "grey"),
               panel.border = element_rect(fill = NA, colour = "grey"))

GT2 <- ... # the same for Mixed-conifer stands
GT1 <- ... # the same for Mixed-hardwood stands

grid.arrange(GT4,GT3,GT1,as.table= T ,nrow=3,
   main=textGrob("Influence of Foliage mass in 5-year Diameter Growth \nof Douglas-fir by
         type of Stand",
   gp=gpar(fontsize=16,font=3)))
```

APPENDIX II. PICTURES

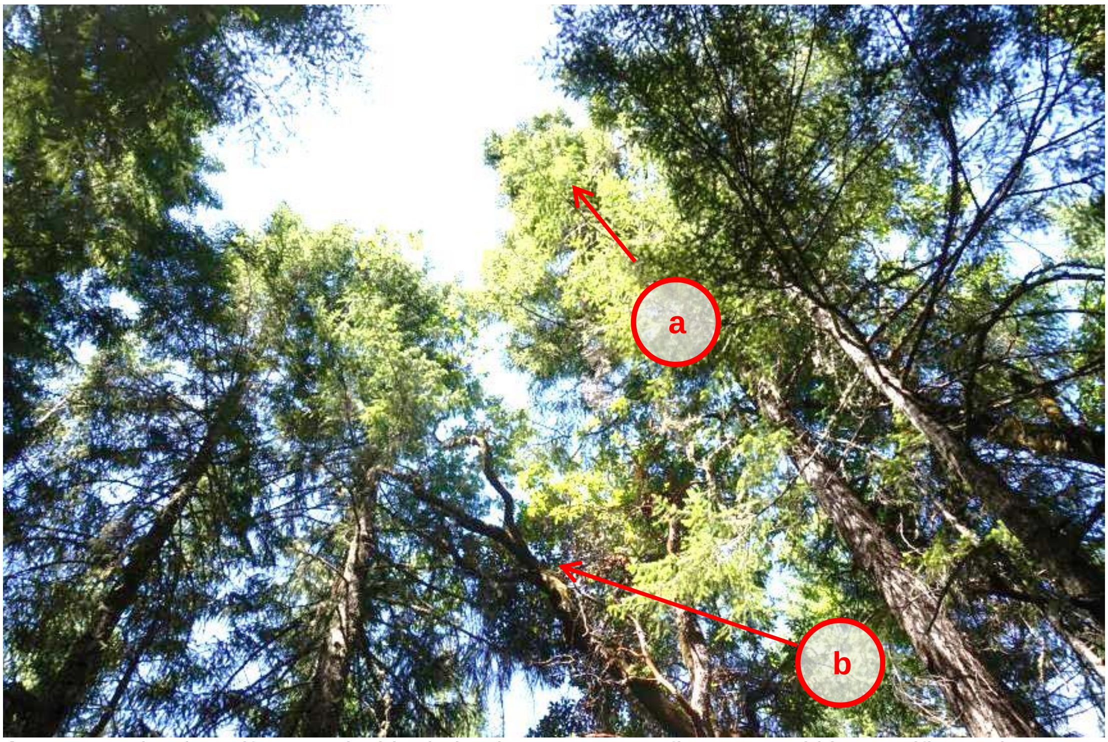
Picture 1. a) Cone of Douglas-fir, b)Cone of Sugar Pine and c) Cone of Ponderosa pine.

Picture 2. Regeneration of Ponderosa pine and Douglas-fir.

Picture 3. Panoramic of one of the study stands.

Picture 4. Pacific madrone.

Picture 5. Crown of a) Douglas-fir and b)Pacific madrone.



Picture 6. Mixed-conifer stand with a) dominant Douglas-fir trees and b) a pacific madrone over its crown.

Picture 7. Douglas-fir tag.

Picture 8. Views from the study area.

Picture 9. Mixed stand with Douglas-fir and red alder.

Picture 10. Doug Maguire and Eladio Cornejo during a core job in one of the new study plots.