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Applying the Prediction of Four-Year Height Growth of Douglas-fir and Ponderosa pine Saplings to an Existing Growth Simulator

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By

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Chairperson: Kelsey Stephen Milner, Ph.D. KSM

Seedling and sapling development is a critical descriptor of future stand structure and growth. Very little information currently exists about small tree growth and its interaction with site and competing vegetation in the inland northwest.

Using a database constructed from a study by the Inland Northwest Growth and Yield (INGY) cooperative, the effects of site and competition on small tree height growth in the inland northwest are investigated. First by utilizing a log-linear approach to investigate the relationships between site and competition and then a non-linear approach to estimate four year height growth of two species, Douglas-fir *(pseudotsuga menziesii)* and ponderosa pine *(pinus ponderosa)*. Finally, the selected prediction equations are incorporated into an existing growth simulator, Forest Projection and Planning Systems (FPS), as an illustration of calibration.

The log-linear approach is somewhat successful in showing the simple linear relationships between height growth and competition. The non-linear model describes the existing data well and shows promise in estimating future height growth.

Acknowledgements

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It would be inappropriate to continue without thanking Dr. Stuart Bliss and Bowen Keller for their statistical and mathematical help and guidance.

On a personal note, I have had two of the finest teachers imaginable in my life, which is two more than most people, Dr. Kelsey Milner and Bowen Keller. They have taught lessons that shaped both who I am now and who I will become. Both have taught by example and with great care, and I have no possible words to convey my appreciation. I would also like to thank Matthew Tunno for starting the ball rolling.

All future positive and operational results of this thesis are the product of all these people, any and all mistakes are mine alone.

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INTRODUCTION:

Predicting or estimating the growth dynamics of a forest or stand of trees over time has long been a challenge for foresters. With the advent of the personal computer, computer software and technology, forest growth models have been expanding in both power and application over the past few decades. There is not, however, a good model for small tree growth that takes into account the effects of non-tree vegetation.

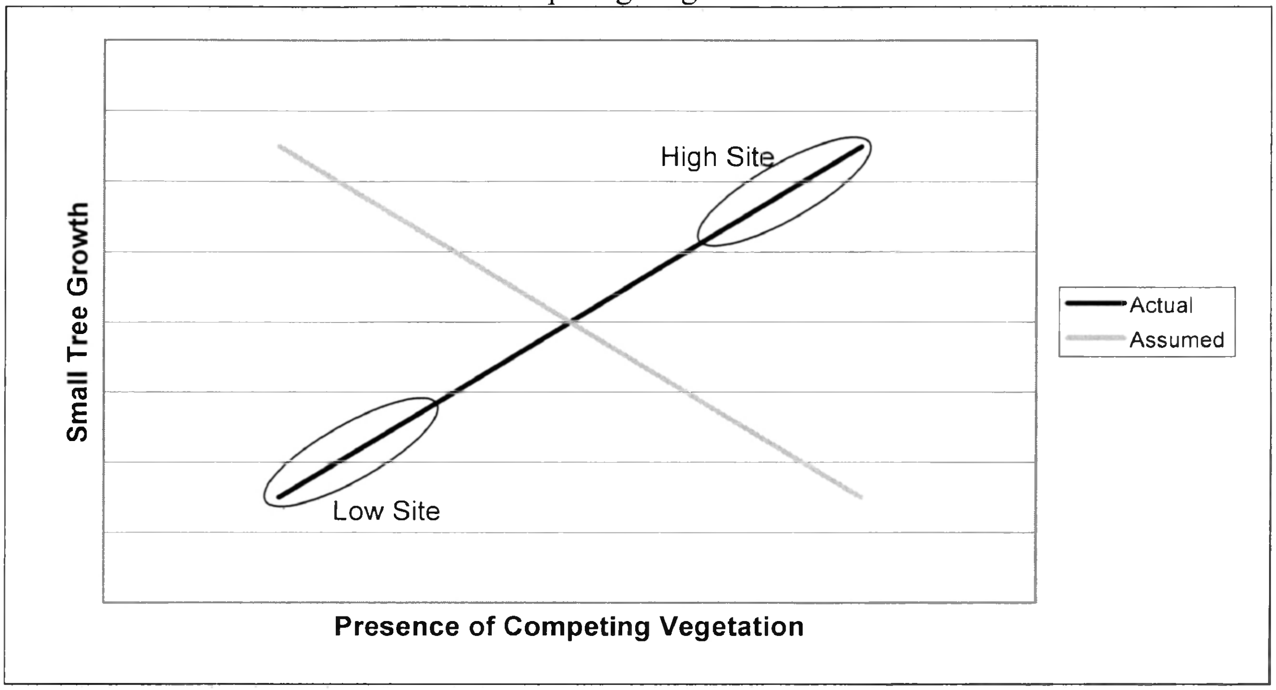
Traditionally, most models were deterministic, empirical, and distance independent like FVS (Stage 1973), CACTOS (Wensel and Biging 1988), CRYPTOS (Wensel et al.1987), and ORGANON (Hester et al. 1989). Recently, much research has been done with stochastic models such as SIMPLE (Chew 1995) and mechanistically based programs such as the Forest BGC (Running and Coughlan 1988), Biome BGC (Running and Hunt 1993) or Stand BGC (Milner and Coble 2003) models. Most of these distant independent models indirectly incorporate spatial and structural data through stand level variables applied equally to trees throughout the stand. This approach does not realistically represent the clumpy, patchy structure of mixed-species multi-aged forests. One model that does address the spatial attributes of a stand is Forest Projection and Planning Systems (FPS) (Arney 1995), which is one of the first truly distant dependent forest growth modeling system to be operationally useful.

Almost all of these models have focused on large tree growth and most of the data collected has been about large trees (greater than twenty feet in height) (Powers et al 1989; Loveall 2000).

A critical time in stand development is in the seedling survival and small tree establishment period (Smith 1986; Stewart 1987). Until recently very little research has been conducted in this area (Wang et al. 1995; Milner and Coble 1995b). One crucial area of study is the effect of competing herbaceous vegetation and grasses on the growth of small trees. In western Montana this competition affects small tree growth (Milner 1997; Carter et al 1984). Keyser and Milner (1998) found that reducing competing vegetation through chemical and mechanical procedures increased the survival and growth of ponderosa and lodgepole pine (Keyser and Milner 1998).

Forest growth models for small trees, which analyze and incorporate the interactions of site, understory non-tree vegetation, and overstory competition are lacking especially in the Inland Northwest. In the mid 1990s the Inland Northwest Growth and Yield Cooperative (INGY) began a comprehensive study named the Small Tree Competing Vegetation (STCV) study. This INGY study formulated a sampling design of permanent plots in 1997 for the purposes of 1) generating data to model small tree growth in the presence of competing vegetation and overstory trees and 2) to model competing vegetation growth in the presence of both small and overstory trees. One of the problems the INGY study addressed is that in many data sets, growth increases with increasing competition from shrubs, forbs, and grasses (Walstad and Kuch 1987) (Figure 1).

Figure 1. Actual and Assumed Trends in Small tree Growth in the Presence of Competing Vegetation



This led to much discussion of the multicollinearity of site quality and competing vegetation affecting small tree growth. Perhaps on the high quality sites both vegetation and trees were not limited and not actually competing due to the abundance of water, nutrients, etc., and that on the lower quality sites there was so much competition due to the lack of these nutrients, that neither trees nor competing vegetation grew well (Loveall 2000). With this idea in mind, the sampling design of the STCV study attempts to decouple the effects of competing vegetation and site quality through various levels of vegetation control on each site.

Preliminary studies have shown that trees are essentially unaffected by competition from non-tree vegetation after reaching 20 feet in height, depending on species (Keyser 1998; Arney 1996). It was also found that small tree growth does increase early on in its life, and reaches its maximum growth rate earlier due to vegetation control (Keyser 1998). The study therefore focuses on trees that at the time of installation of the permanent plots were less than 20 feet tall. Loveall's (2000) thesis found that utilizing competing vegetation as an independent variable after decoupling its effects from site quality is promising in modeling small lodgepole pine height growth.

Early studies of the STCV data have shown several interesting results. Krebs (2003) measured the amount of photosynthesis occurring in trees on both low and high competing vegetation on two different sites, one dry and the other wet. Using percent cover as the measure of competition on tree centered plots, he found a very significant increase in photosynthesis, longer growing season, and decreased water stress between the levels of vegetation, with the more significant results on the dry site, which seems logical (Figure 2 and Figure 3)

Figure 2. Summer Net Photosynthesis for Wet Site (Krebs 2003)

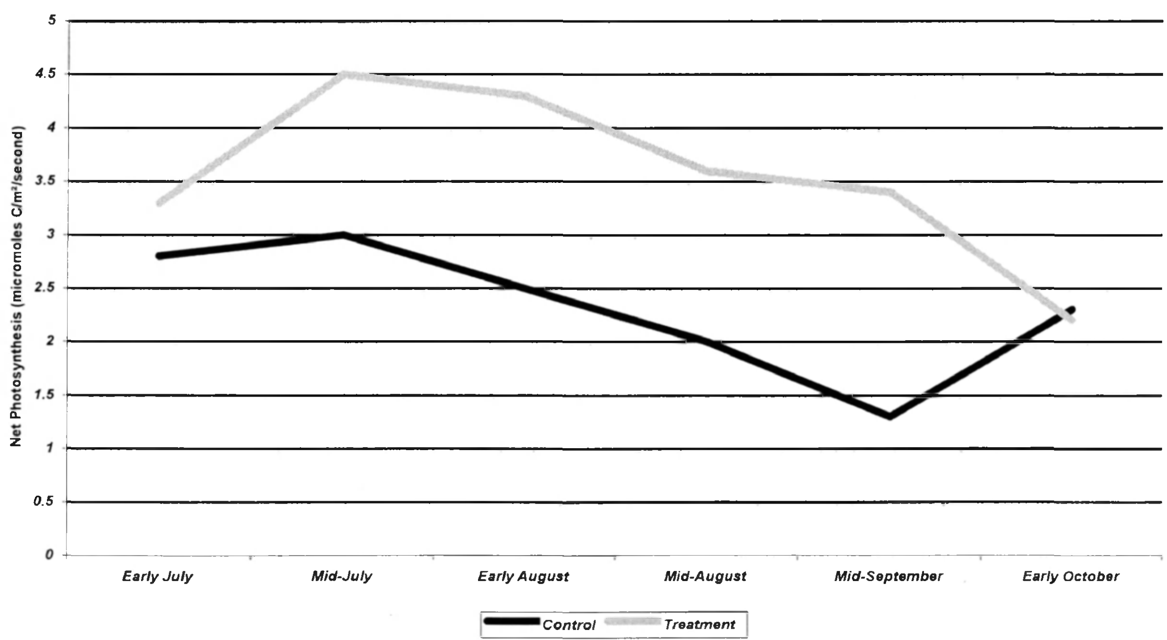
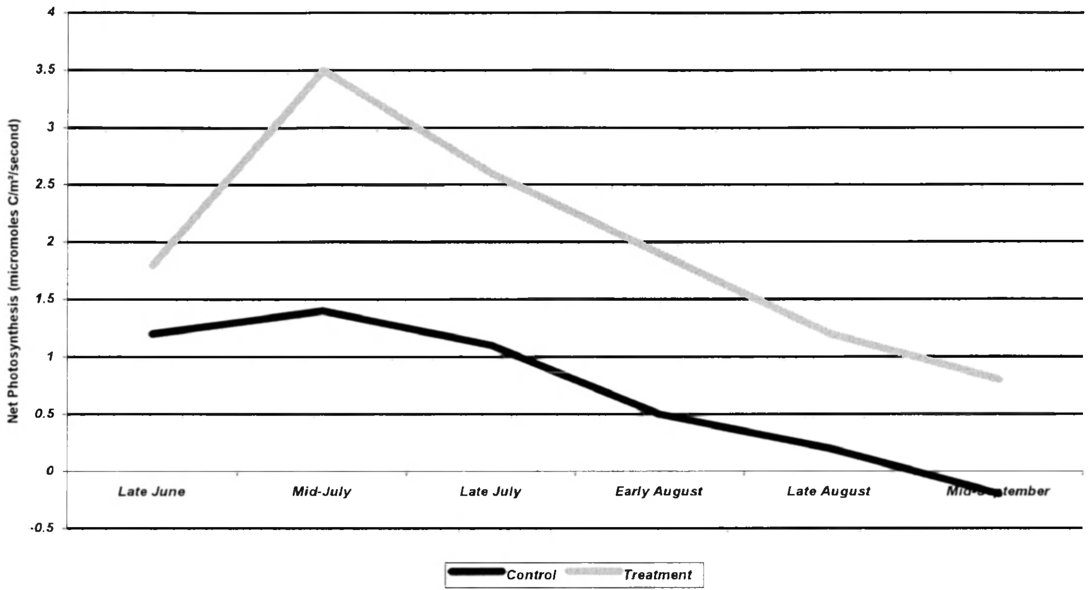
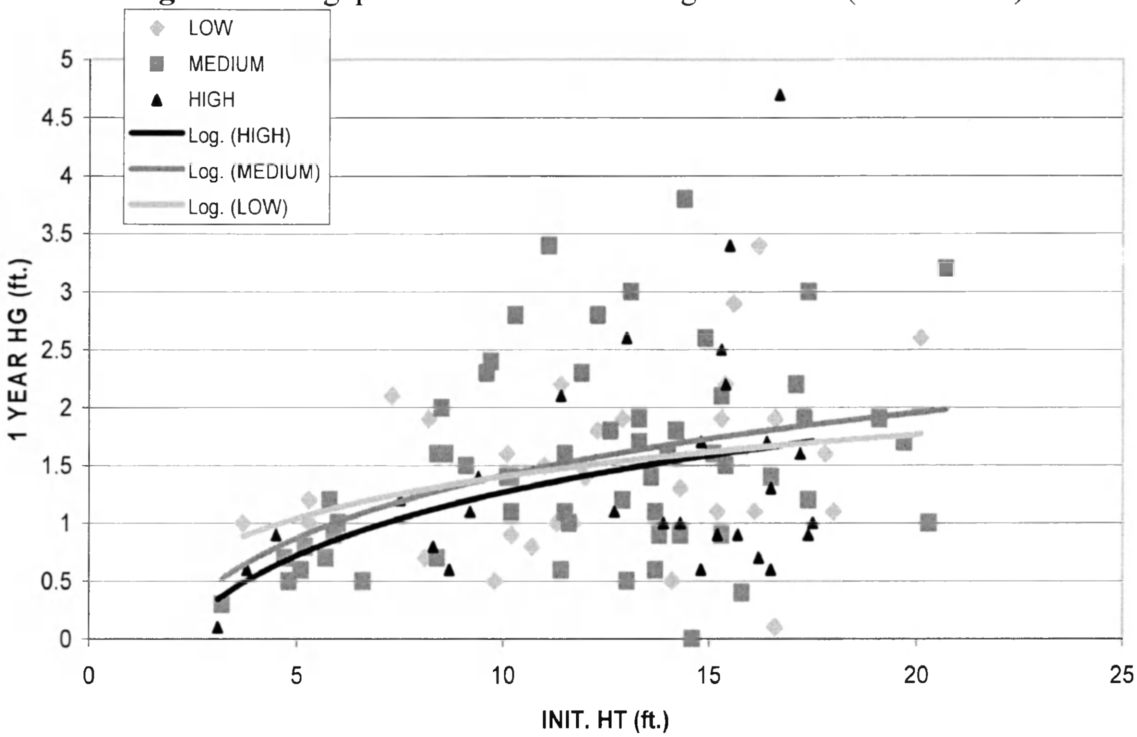


Figure 3. Summer Net Photosynthesis for Dry Site (Krebs 2003)



Farris (2003) presented some preliminary graphs of tree height growth in response to levels of competing vegetation, which was calculated with a distance independent approach, applying one half acre plot levels of vegetation volume estimates to the individual trees. After one year of height growth response data there was very little to no significance in the data. Figure 4 shows a typical graph of one year height growth as stratified by plot level estimates of vegetation competition.

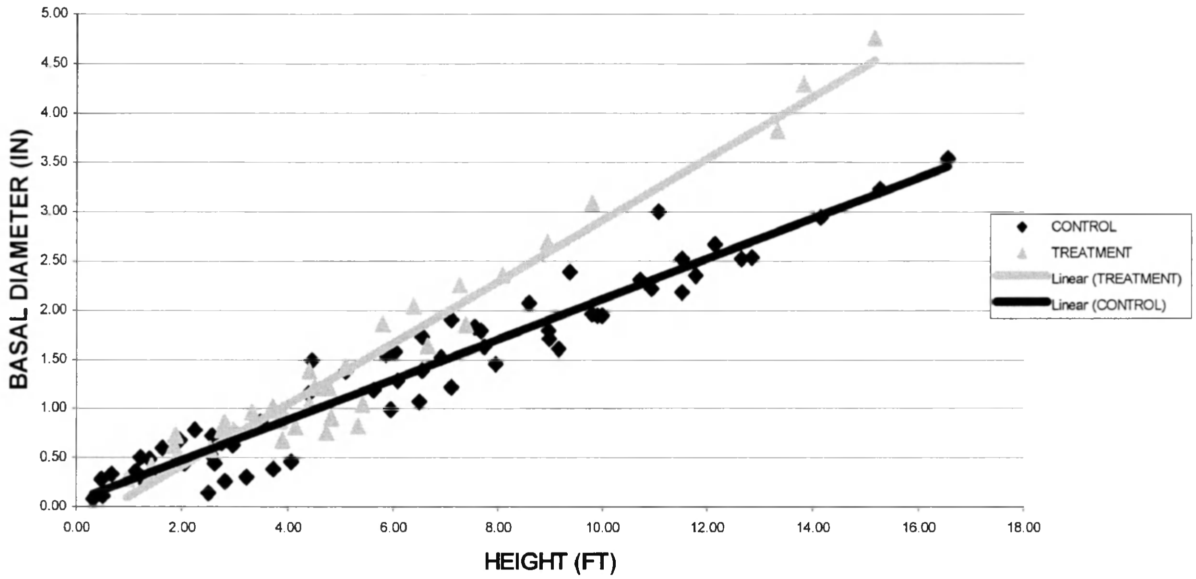
Figure 4. Lodgepole Pine One Year Height Growth (Farris 2003)



After observing an increase in photosynthesis due to treatment, and not observing a response in one-year distance independent height growth due to treatment, a stem analysis study was implemented in 2003 to see if there was some response in diameter growth. Basal diameter measurements taken from cookies cut from the stems and height growth measurements taken at the growth nodes along the stem of ponderosa pine and Douglas-fir trees were obtained across a range of heights from both control and treatment plots. Due to the limitations of time and lack of sites with multiple years of response to treatment, only four sites were studied, three of which had two years of response data and one site (Cemetery Road) had three years of response. There was no significant response due to treatment after two years but the three years response did show a significant increase in diameter due to treatment (Goodburn 2003). Figure 5 a scatter diagram of cross sectional data of diameter in inches vs. the height in feet of individual trees at

Cemetery Road. This graphical representation shows a significant increase in basal diameter due to treatment (i.e. at a height of 12 – 14 feet, there is almost a full inch increase in basal diameter).

Figure 5. Height/Basal Diameter Pairs of Ponderosa Pine at Cemetery Road (Goodburn 2003)



Prior work suggests that growth responses to vegetation control of small trees are best analyzed using a distance dependent measurement of competition and that diameter or volume growth should be used as the response variable. At this time, however, the data set being utilized does not have enough detailed basal diameter measurements available for study, but soon will in a few years time. Therefore, modeling height growth using distance dependent variables with four years of response data is a logical direction to follow.

OBJECTIVES:

The first objective is predicting four-year height growth of ponderosa pine and Douglas-fir as a function of non-tree competing vegetation variables based on a distance dependent approach.

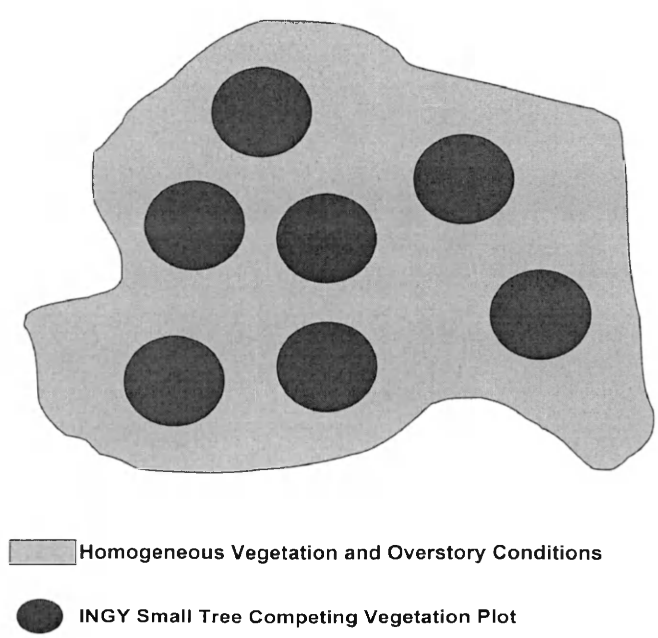
A second objective is to analyze the data in terms of years needed to reach 20 feet in height (at which trees appear to grow out of the zone of competition from understory plants) and use these results to calibrate the small tree model in FPS.

METHODS:

INGY data collection

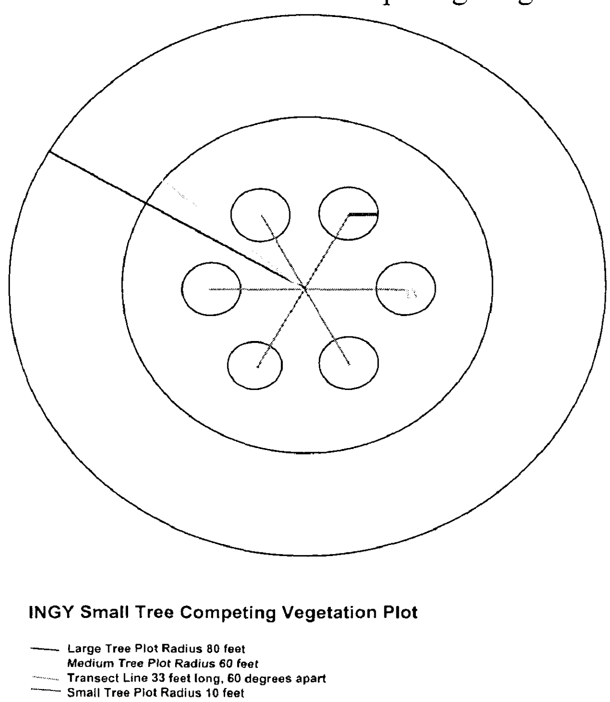
The INGY STCV sampling procedures require that a stand of relatively homogeneous overstory density and site quality be selected in one of two general forest types (PPmix or DFmix) that is at least five acres in size. Cooperators must also be willing to leave the site idle from harvest for at least ten years. A sampling matrix of a range of site qualities and overstory density combinations predetermined by the cooperative insures a wide degree of variation between installations.

Figure 6. INGY Small Tree Competing Vegetation Site



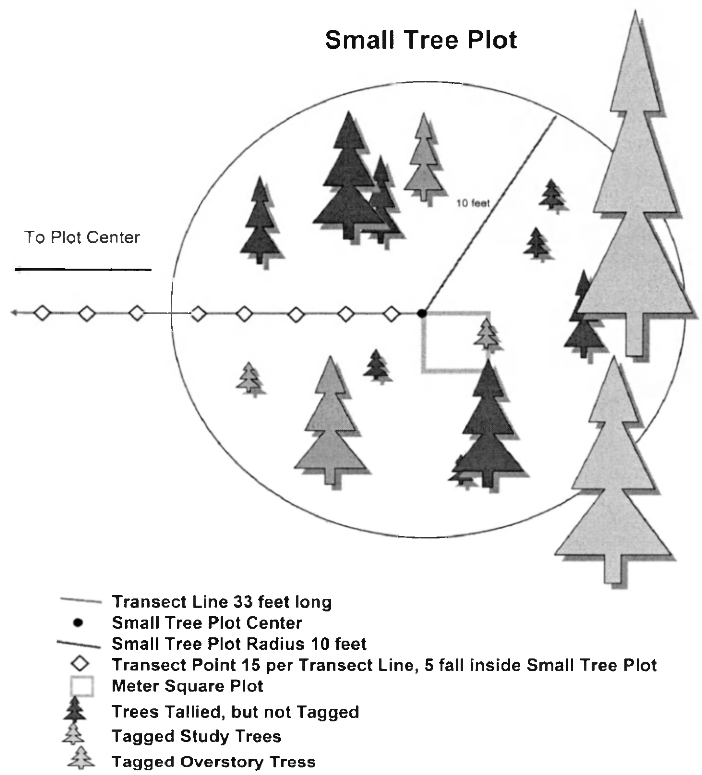
Seven plot centers are subjectively installed to insure similar conditions of overstory density and understory vegetation (Figure 6). Each plot has several plots nested within it. The large tree plot is 80 feet in radius from plot center (0.46-acre). Similarly the medium tree plot is 60 feet in radius (0.26-acre). Six 33 foot long transect lines radiate from plot center at 60 degree intervals, each with 15 sampling points, two feet apart, starting after the first two feet. One foot after the last stop on each transect a pipe marks the center of the small tree plot (STP), which is a ten-foot radius plot (0.007-acre). A one-meter square quadrat is also established at this pipe (Figure 7). The first transect and STP are always installed directly upslope, randomly defining the placement of the other transects.

Figure 7. INGY Small Tree Competing Vegetation Plot



At an installation, the overstory trees (trees larger than 3.5 inches in DBH) are tagged, stem mapped, and measured. All trees from 3.6 inches to 10.5 inches in DBH are measured on the 60-foot radius plot, while trees larger than 10.5 inches in DBH are measured on the 80-foot radius plot. Species, tree number, DBH (± one-tenth inch), height (± one half-foot), height to base-of-crown, height to lowest contiguous living whorl, sapwood thickness, bark thickness, crown width, and any damages are recorded on these trees.

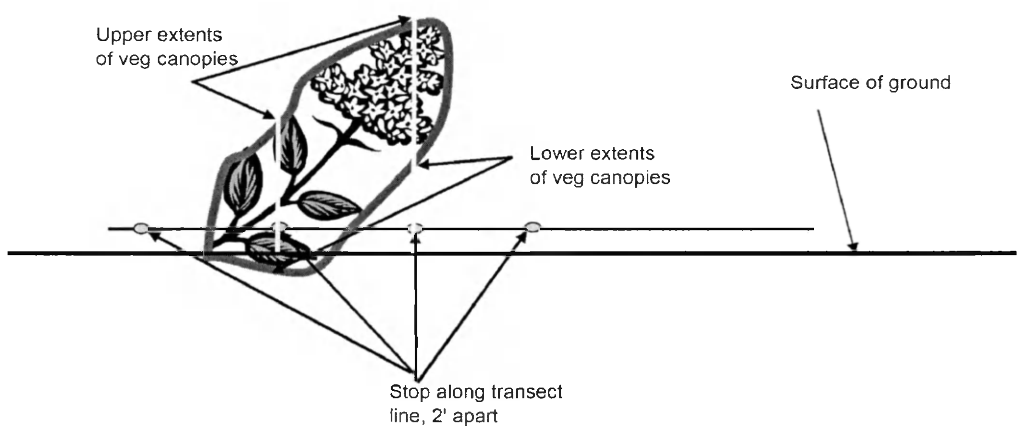
Figure 8. INGY Small Tree Plot



Small tree plots (six per study plot) are centered 33 feet from plot center (Figure 8). Tolerant species greater than or equal to 0.5 foot in height and intolerant species greater than or equal to one foot in height and all trees up to a DBH of less than 3.5 inches are tallied by species in two-foot height classes on these plots. These tallied trees are then sub-sampled across the range of size and species to achieve a number of tagged trees of at least 200 trees per acre. These sub-sampled trees are assigned a tree number, measured for species, basal diameter DBH, total height, 3 years of previous height growth, height to base-of-crown, height to lowest contiguous living whorl, crown width, damages, and stem mapped.

Along the 33-foot transect lines lie 15 sampling points. At each point the upper and lower extent of height of the canopy of individual shrubs and forbs are measured vertically by species and by individual plant (Figure 9). At each of these points a six-inch by six-inch square is affixed at the sample point in the bottom left corner. In this manner ocular estimates of projected leaf area of grasses, average blade height, and species are recorded, along with ocular estimates of percentage of ground cover (i.e. soil, rock, duff, coarse woody debris and moss/lichen). With the six transect lines per plot and 15 points per line; there are 90 of these sampling points per plot.

Figure 9. Vegetation Canopy Measurements



The meter square plots located at the terminal end of each transect line are used to measure both vegetation and tree regeneration. Ocular estimates of percent cover, dominant species, and average height to top and base are recorded for high shrubs (those greater than a meter in height), low shrubs (those less than a meter in height), forbs and grasses. The number and species of tolerant tree species less than half a foot in height and that of intolerant species less than one foot in height are also recorded. There are six-meter square plots per main study plot.

At the time of installation, date, field crew, slope, aspect, elevation, habitat type, site index, and GPS coordinates are taken for each plot. The distance and azimuth from plot to plot and fairly detailed directions to the site are recorded and mapped.

Immediately following installation, five of the seven plots are randomly assigned to a herbicide treatment. Treatment types have varied across the sites due to high water tables, sensitive overstory species (Western Larch), physical variations in terrain, etc. These variations consist of the application of the herbicides Pronone (a granular), Oust (a liquid), with, at times, the addition of hand lopping and grubbing.

Remeasurements take place the first, second, and fifth years following initial treatment.

At the time of remeasurement there are only two deviations from the installation measurement procedures. Firstly, the overstory trees are not remeasured. Secondly, the past three years growth of small trees becomes irrelevant due to redundancy and is therefore omitted from the measurement procedures.

After the first remeasurement, three of the initial five treated plots are randomly selected to become "Garden of Eden plots". These three plots are retreated at every time the site is revisited as needed to achieve maximum reduction in understory vegetation.

Therefore of the seven plots per site, two are control and have no treatment (initial levels of competing vegetation), two receive a one-time treatment (dramatically reducing vegetation early in the study), and three plots are continuously treated (meaning that they contain little to no competing vegetation). It is with this continuous variability in competing vegetation across one site, repeated across many sites, that the effects of site quality can be decoupled from competing vegetation on small tree height growth.

Twenty-four sites over the seven-year period of 1998 through to 2004 provide the data for this study. Eight of these sites yield four years worth of response data in height growth.

Database construction (i.e. methods used to create spatial data, etc.)

The INGY STCV sampling design was created to capture distance independent one half-acre plot level estimates of vegetative competition. This means that every subject tree on a given plot at a given site would receive the same one half acre plot average estimates of competition, from overstory density to competition from shrubs, forbs, and grasses.

The desired goal of a distance dependent database is to assign each subject tree unique vegetative estimates of competition in the immediate proximity of that subject tree. This approach hopefully will reduce the noise in the data examined in Farris' (2003) distance independent analysis. Altering the existing database created a unique challenge.

In the distance independent analysis the transect based estimates of shrubs and forbs competition were calculated by measuring the percent cover from the ninety points on the six transect lines. The percent cover by life form was then multiplied by the average canopy depth to create an average cubic volume of canopy for that half acre. The grass canopy volume was calculated by taking the average percent cover in the six inch by six inch squares of all ninety points and multiplying by the average blade height for those points yielding a one half acre average cubic foot grass volume.

The other method of estimating canopy volume for non-tree vegetation involved using is the ocular estimates from a square meter. In previous analyses these data were utilized by calculating the percent cover of shrubs, forbs, and grasses and multiplying them by the average canopy depth on each STP; the average of these six-meter squares per plot is then assigned as that plot's one half-acre estimate of cubic foot per acre canopy volume. In both the transect based and meter square estimates, the totals of the different life forms are composed of the non-weighted sum of these components.

The distance dependent database employs these measurements in much the same way except that the data are summarized at the STP level (0.007 acre) rather than of the main one half acre plot level. This is accomplished rather simply with the meter square estimates by not averaging all six per main plot and just using the individual meter square estimates for each STP. Altering the transect based estimates to more spatially explicit variables was more complicated. The last five transect points on each line fall within the ten-foot radius STP. These points are then used in the same fashion as in the distance independent database except that the averages are by STP, using five points, not ninety. While this methodology does not create truly distance dependent vegetation variables, it does improve the description of the competition in the immediate proximity of the each sample tree.

The variables describing tree-to-tree competition are more complex. Since all tagged study and overstory trees were stem mapped using polar coordinates at the time of installation, a simple procedure to convert to rectangular coordinates was performed. The primary tree competition variable created is a distance dependent measure of competition called Competitive Stress Index (CSI) (Arney 1973). CSI is an individual tree centered measure of tree-to-tree competition. It is based on the idea that a tree's open grown crown width is a good indicator of potential growing space. Many studies have been done to relate a tree's diameter at breast height (DBH) to what its crown width would be if it were under no competition (open grown). The equations used here are those of Arney (1995).

$$Crown\_Width = 4.02 + (2.12 * DBH) - (0.02 * DBH^2) \quad \textbf{[1]}$$

Using Equation 1, open grown crown width is estimated for all stem mapped trees. The estimated rown width is then converted into an area. Using the rectangular coordinates, all overstory trees' potential crown areas that overlap the study tree's crown area are calculated, summed, added to the study tree's own crown area, and then divided by the study tree's crown area and reported as a percentage. As a result the lowest CSI a tree can have is then 100%. To represent each subject tree's overstory competition a variable was calculated minus the subject trees crown area, named CSI overstory. The same process was followed to quantify the competition of the other tagged study trees on that particular subject tree, named CSI understory.

The remaining tree competition (trees tallied at the STPs that were not stem mapped) is described by a variable called Crown Competition Factor (CCF) understory. CCF is a distant independent measure of stand density that is based on open grown crown areas. These crown areas are summed over the acre and divided by the square feet in an acre (43,560). This ratio is then reported as a percentage. Since all tagged trees are included in the tally, an effort was made to remove all tagged trees whose influence has already been accounted for in CSI understory. To get the DBH for tallied trees on the STPs, a regression equation, by species and by site, of the relationship between the mean height of the two-foot height classes and a DBH was then created. These mean DBHs were then used to create the open grown crown areas for each two-foot size class, summed, and divided by the square footage of the STP.

It should be noted that with respect to these tree-to-tree competition variables, no tree's influence is recorded twice and the variables are all in the same units and therefore additive, permitting the creation of a fourth variable called total tree competition. For a complete list and definitions of these variables please see Appendix A.

Modeling Methods

• *Log-Linear Models*

For the initial analysis, the author attempts a linear regression approach by each species (ponderosa pine and Douglas-fir), to identify possible predictors of height growth and the simple linear relationships between these variables. Preliminary analysis shows a lack of homogeneous variance across the data for both species. With this violation of the assumption of homoscedastisity, the response variable (four-year height growth) requires a natural log transformation. Following a natural log transformation of the dependent variable, the distribution of residuals as a function of the fitted values appears homogeneous. After detecting the appropriate vegetative competition variables to include, a model assessing the significance of the possible interaction variables was produced.

• *Non-Linear Models*

After the appropriate predictor variables are identified, non-linear regression was used to model the relationship between height growth and competition variables. In considering a model form for this data, to estimate height growth, one might consider the shape of a tree's height growth curve. The Height/Age curve usually follows a sigmoid shape. Height growth, the first derivative, starts off slowly, increases to a maximum rate, and at some point in the tree's life (at the point of inflection of the Height/Age curve), flattens out asymptotically and then declines.

With the INGY STCV data set, initial height is never greater than 15 feet tall, which leads one to assume that throughout the course of a four-year growth period, these trees will not have reached the inflection point of the Height/Age curve.

The Chapman-Richards function can be used to represent the sigmoid shaped biological growth curve namely:

$$E(y) = \beta_1 * \left(1 - e^{(\beta_2 * X_1)}\right)^{\beta_3} \qquad \textbf{[2]}$$

Where E(y) is the dependent variable, in this case, four-year height growth. The maximum (asymptote) four-year height growth (which is determined by site quality) is represented by β_1 while the rest of the equation represents the proportion of that maximum. Initial height represents the scale of the shape of growth and therefore is the independent variable next to the β_2 parameter and the competitive effects of tree and vegetation competition variables should somehow be represented next to the β_3 parameter, which is the parameter that effects shape. This leads to a model formation of:

$$E(y) = (\beta_1 * X_1) * \left(1 - e^{(-\beta_2 * X_2)}\right)^{((\beta_3 * X_3) + (\beta_4 + X_4))} \qquad \textbf{[3]}$$

Where:

$E(y)$	=	Expected four year height growth
β_1	=	Site parameter
β_2	=	Initial tree height parameter
β_3	=	Total tree competition parameter
β_4	=	Vegetation competition parameter
X_1	=	Site Index
X_2	=	Initial tree height
X_3	=	Total tree competition
X_4	=	Vegetation competition

After this analysis an investigation of other possible models was performed. Most significantly if adding an y-intercept will improve the model, resulting in the equation:

$$E(y) = \beta_0 + (\beta_1 * X_1) * \left(1 - e^{(-\beta_2 * X_2)}\right)^{((\beta_3 * X_3) + (\beta_4 + X_4))} \qquad \textbf{[4]}$$

Where:

$E(y)$	=	Expected four year height growth
β_0	=	Y-Intercept
β_1	=	Site parameter
β_2	=	Initial tree height parameter
β_3	=	Total tree competition parameter
β_4	=	Vegetation competition parameter
X_1	=	Site Index
X_2	=	Initial tree height
X_3	=	Total tree competition
X_4	=	Vegetation competition

Another attempt to explain more of the variation will be to assess the significance of interaction terms were added to the equation.

Methods of creating years to 20 feet in height database

Manipulation of the INGY data set is required to compare these data to the FPS Species Library. An FPS Species Library is an external text file of necessary coefficients for the growth model. Modification to this file yields changes in growth increment, mortality, etc. of the FPS outputs. With all critically damaged trees removed, there are not enough trees left to explore the treatment plots. Also, since little to no quantifiable site preparation or animal control was performed on these sites, I chose to compare FPS's predictions with no animal control, brush control, or site preparation against the INGY STCV control plots results only.

This data set is then manipulated so that each record contains the initial and ending heights, species, site index, and the difference in years from the first to the last measurement. Any tree whose initial height was greater than twenty feet was outside the range of the FPS small tree growth model and therefore removed from the dataset.

Estimating the years to twenty feet is necessary because no ages were recorded in the INGY dataset. Using two points in time of a tree's height growth and knowing the time between this growth, places this tree on a predefined curve whose trajectory estimates the years to twenty feet. This predefined curve used in FPS is a power function with an exponent of 1.6 on relative age, that Arney (2005) describes as the set of anamorphic curves of growth trajectories for those trees under twenty feet in height after which the trees follow the actual site curves. Relative age is the estimated age of the tree at the initial height when the tree's growth trajectory falls on the predefined site curve. Once calculated the means of years to twenty feet by species, region, and site class are grouped and averaged.

These years to twenty feet are then compared to the Species Library in FPS. Arney's estimates of animal control, brush control, and site preparation are then subtracted from these years to twenty feet. Only site qualities of 15 and 20 meters (49 and 66 feet) could be matched to the range of the INGY STCV data for the species Douglas-fir and ponderosa pine. The data was collected in two different regions of the FPS Library, Western Montana/Northern Idaho (Region 14) and Eastern Washington (Region 13). The steps to calibrate FPS are in Appendix C.

RESULTS AND DISCUSSION:

Log-Linear Regressions:

• *Ponderosa Pine*

Using the natural log of height growth as the dependent variable results in a model with an arithmetic R-square of 0.513 and a standard error of the estimate of 1.225. Table 1 and Table 2 show the results:

Table 1. ANOVA Table for Ponderosa Pine

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	87.813	5	17.563	123.148	.000
	Residual	69.025	484	.143		
	Total	156.837	489			

Table 2. Coefficients of Linear Regression for Ponderosa Pine

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.459	.185		2.478	.014
	Site Index	1.084E-02	.003	.140	4.058	.000
	CSIunderstory	-1.781E-03	.000	-.236	-7.416	.000
	CSIoverstory	-2.717E-03	.001	-.168	-5.278	.000
	CCFunderstory	-3.412E-04	.000	-.422	-13.294	.000
	Initial Height	9.592E-02	.007	.422	13.943	.000

a Dependent Variable: LNHTGR

Notice that none of the non-tree vegetation variables have been added. Each variable available for analysis added singularly results in the following p-values:

Table 3. Vegetation Variable P-Values for Ponderosa Pine

Vegetation Variable	P-value
First Total Transect based Vegetation	0.926
First Transect based Shrub	0.826
First Transect based Forb	0.517
First Transect based Grasses	0.875
First Meter Square based Total Vegetation	0.005
First Meter Square based Grasses	0.033
First Meter Square based Forb	0.110
First Meter Square based Shrubs	0.021
Ending Total Transect based Vegetation	0.375
Ending Transect based Shrub	0.150
Ending Transect based Forb	0.050
Ending Transect based Grasses	0.890
Ending Meter Square based Total Vegetation	0.946
Ending Meter Square based Grasses	0.008
Ending Meter Square based Forb	0.008
Ending Meter Square based Shrubs	0.971

Those variables showing a significance of less than 0.05 were then added in a stepwise regression yielding a model with an arithmetic R-square of 0.533 and a standard error of the estimate of 1.203. Table 4 and Table 5 show the results:

Table 4. ANOVA Table for Ponderosa Pine 2nd Run

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	90.599	8	11.325	82.238	.000
	Residual	66.238	481	.138		
	Total	156.837	489			

Table 5. Coefficients of Linear Regression for Ponderosa Pine 2nd Run

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	**.412**	**.190**		**2.170**	**.031**
Site Index	**1.66E-02**	**.003**	**.150**	**4.039**	**.000**
CSIunderstory	**-1.728E-03**	**.000**	**-.229**	**-7.252**	**.000**
CSIoverstory	**-2.747E-03**	**.001**	**-.170**	**-5.327**	**.000**
CCFunderstory	**-3.507E-04**	**.000**	**-.434**	**-13.656**	**.000**
Initial Height	**9.828E-02**	**.007**	**.432**	**14.483**	**.000**
First Meter Square based Total Vegetation	**-3.144E-06**	**.000**	**-.084**	**-2.450**	**.015**
Ending Meter Square based Grasses	**-2.656E-06**	**.000**	**-.064**	**-2.080**	**.038**
Ending Meter Square based Forbs	**9.745E-06**	**.000**	**.085**	**2.739**	**.006**

a Dependent Variable: LNHTGR

One can see that the R-square for the first model is 0.513, as opposed to the R-square of the second model of 0.533. In adding these variables to the equation in the second model only 2 percent more of the variation in the natural log of height growth is explained and the mean square error is barely reduced. In Table 5 one can see that the coefficients behave as one would expect with the competition variables, both tree-to-tree and non-tree vegetation, are negative, except for the ending meter square based forb variable, which is positive.

The model generated to determine the usefulness of interaction terms was created in a stepwise regression, after the variables of Initial Height, Site Index, CSI understory, CSI overstory, CCF understory, and for parsimonious reasons just First Meter Square based Total Vegetation are fixed. The Interaction variables created for this analysis are in Table 6.

Table 6. Interaction Variables

Variable Name	Variables interacting
SI x Veg	**Site Index and First Meter Square based Total Vegetation**
CSI Over x Veg	**CSI overstory and First Meter Square based Total Vegetation**
Veg x Total Tree	**First Meter Square based Total Vegetation and Total Tree Competition**
CSI Under x CSI Over	**CSI overstory and CSI understory**
SI x CSI Over	**Site Index and CSI overstory**
SI x Total Tree	**Site Index and Total Tree Competition**
SI x Total Tree x Veg	**Site Index and Total Tree Competition and First Meter Square based Total Vegetation**

The results of this yield a model with an arithmetic R-square of 0.539 and a standard error of the estimate of 1.198. Table 7 and Table 8 show the results:

Table 7. ANOVA Table for Ponderosa Pine 3rd Run

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	95.017	10	9.502	73.622	.000
	Residual	61.820	479	.129		
	Total	156.837	489			

Table 8. Coefficients of Linear Regression for Ponderosa Pine 3rd Run

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-.517	.226		-2.287	.023
Site Index	2.678E-02	.003	.345	7.918	.000
CSIunderstory	-1.791E-03	.000	-.237	-7.573	.000
CSIoverstory	-9.212E-03	.002	-.569	-5.072	.000
CCFunderstory	-2.634E-04	.000	-.326	-8.141	.000
Initial Height	.101	.007	.444	15.111	.000
First Meter Square based Total Vegetation	7.068E-05	.000	1.897	5.102	.000
SI x Veg	-1.090E-06	.000	-1.991	-5.177	.000
CSI Over x Veg	1.902E-07	.000	.182	4.295	.000
Veg x Total Tree	-1.020E-08	.000	-.160	-3.283	.001
CSI Under x CSI Over	2.801E-05	.000	.287	2. 815	.005

a Dependent Variable: LNHTGR

While four on these interaction variables did come in significant, their interpretation is unclear due to the sample size of just 491 and not knowing at this time if these interactions are artifacts of the distribution of the data.

• *Douglas-fir*

Following the same procedure as with ponderosa pine, the non-tree vegetation variables excluded, results in a model with an arithmetic R-square of 0.625 and a standard error of the estimate of 1.503. Table 9 and Table 10 show the results:

Table 9. ANOVA Table for Douglas-fir

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	201.724	5	40.345	104.807	.000
	Residual	68.135	177	.385		
	Total	269.859	182			

Table 10. Coefficients of Linear Regression for Douglas-fir

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-4.827	.606		-7.967	.000
Site Index	6.883E-02	.010	.368	6.986	.000
CSIunderstory	8.348E-04	.001	.047	1.174	.242
CSIoverstory	-3.156E-03	.001	-.157	-3.683	.000
CCFunderstory	3.395E-04	.000	.132	3.117	.002
Initial Height	.128	.012	.511	10.349	.000

a Dependent Variable: LNHTGR

Adding each non-tree vegetation variable singularly to this equation gives the following p-values.

Table 11. Vegetation Variable P-Values for Douglas-fir

Vegetation Variable	P-value
First Total Transect based Vegetation	**0.269**
First Transect based Shrub	**0.349**
First Transect based Forb	**0.561**
First Transect based Grasses	**0.180**
First Meter Square based Total Vegetation	**0.097**
First Meter Square based Grasses	**0.860**
First Meter Square based Forb	**0.071**
First Meter Square based Shrubs	**0.089**
Ending Total Transect based Vegetation	**0.216**
Ending Transect based Shrub	**0.210**
Ending Transect based Forb	**0.481**
Ending Transect based Grasses	**0.266**
Ending Meter Square based Total Vegetation	**0.897**
Ending Meter Square based Grasses	**0.133**
Ending Meter Square based Forb	**0.193**
Ending Meter Square based Shrubs	**0.749**

Unlike the ponderosa pine values, none of these variables show any significant effect upon Douglas-fir height growth (Table 11).

The same process of adding interaction terms was performed on the Douglas-fir database resulting in no significant interaction terms indentified.

Non-Linear Analysis:

Using first meter square based total vegetation as the vegetation variable is justifiable as it was the most significant in the exploratory analysis of the log linear regression and it incorporates the sum of the grasses, forbs and shrubs.

Equation 5 shown below is the model used in this analysis.

$$E(y) = (\beta_1 * X_1) * \left(1 - e^{(-\beta_2 * X_2)}\right)^{((\beta_3 * X_3)+(\beta_4 + X_4))} \quad [5]$$

Where:

$E(y)$	=	Expected four year height growth
β_1	=	Site parameter
β_2	=	Initial tree height parameter
β_3	=	Total tree competition parameter
β_4	=	Vegetation competition parameter
X_1	=	Site Index
X_2	=	Initial tree height
X_3	=	Total tree competition
X_4	=	Vegetation competition

• *Ponderosa Pine*

The results of this analysis for ponderosa pine are in Table 12 and Table 13.

Nonlinear Regression Summary Statistics Dependent Variable Four Year Height Growth

Table 12. Summary Statistics for Ponderosa Pine

Source	DF	Sum of Squares	Mean Square
Regression	**4**	**6048.50224**	**1512.12556**
Residual	**486**	**737.26776**	**1.51701**
Uncorrected Total	**490**	**6785.77000**	
(Corrected Total)	**489**	**1493.79839**	

R squared = 1 - Residual SS / Corrected SS = .50645

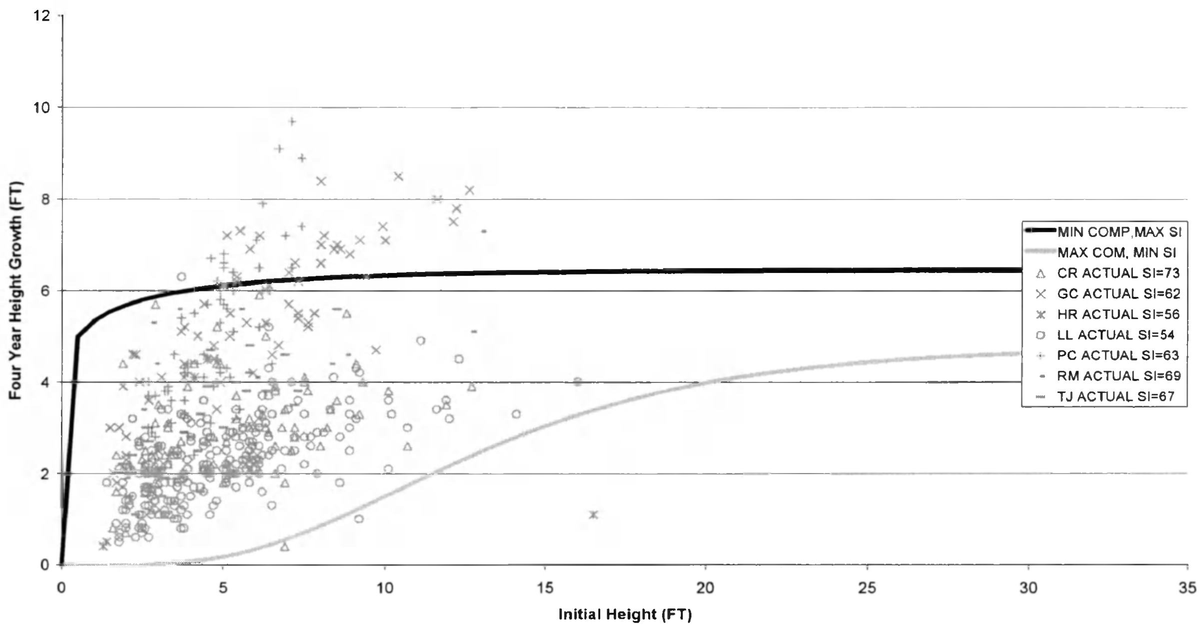
Asymptotic 95 %
Asymptotic Confidence Interval

Table 13. Coefficients of Non-Linear Regression for Ponderosa Pine

Parameter	Estimate	Std. Error	Lower	Upper
B1	**.088404417**	**.002570950**	**.083352869**	**.093455966**
B2	**.177471981**	**.024742281**	**.128856933**	**.226087028**
B3	**.001048590**	**.000150692**	**.000752501**	**.001344679**
B4	**.000010167**	**2.23517E-06**	**5.77500E-06**	**.000014559**

A graph showing the maximum and minimum height growth that this model can predict within the constraints of the collected data, along with the actual observed data by site is in Figure 10.

Figure 10. Maximum and Minimum Range of Non-Linear Model for Ponderosa Pine



The adjusted R square of this model is 0.506, with the coefficients behaving properly (Table 12 and Table 13). Two Sites, however, stand out as not being well described by the model, Grouse Creek (GC) and Pine Creek (PC). Figure 11 shows the graph displaying the effect of tree competition on height growth, with the site index set at the data sets mean of 64 feet and the vegetative competition set at the mean of 10,000 cubic feet per acre. Figure 12 is a graph displaying the effects of vegetative competition on height growth, with the same mean site index of 64 feet and the tree competition set at the mean of 900%.

Figure 11. Ponderosa Pine Non-Linear Model Surface
(showing effects of tree to tree competition)

Mean Site Index= 64 and Mean Vegetation Competition = 10,000 cubic feet per acre

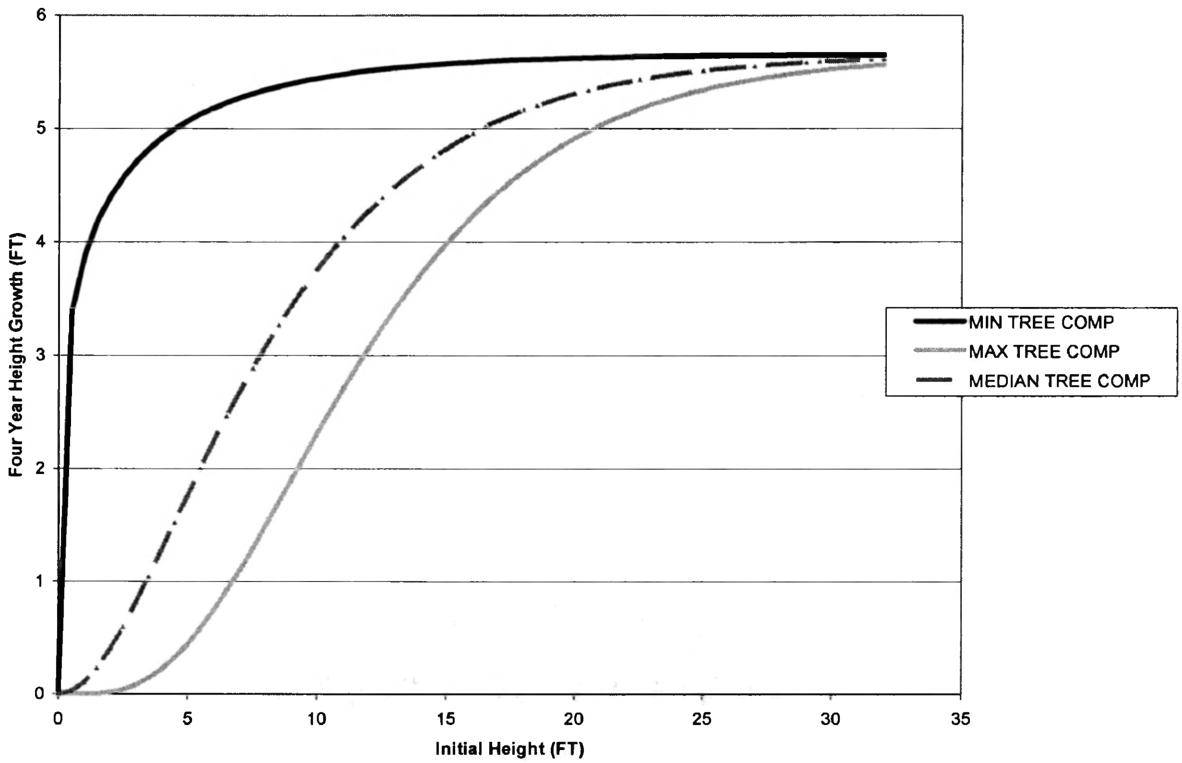
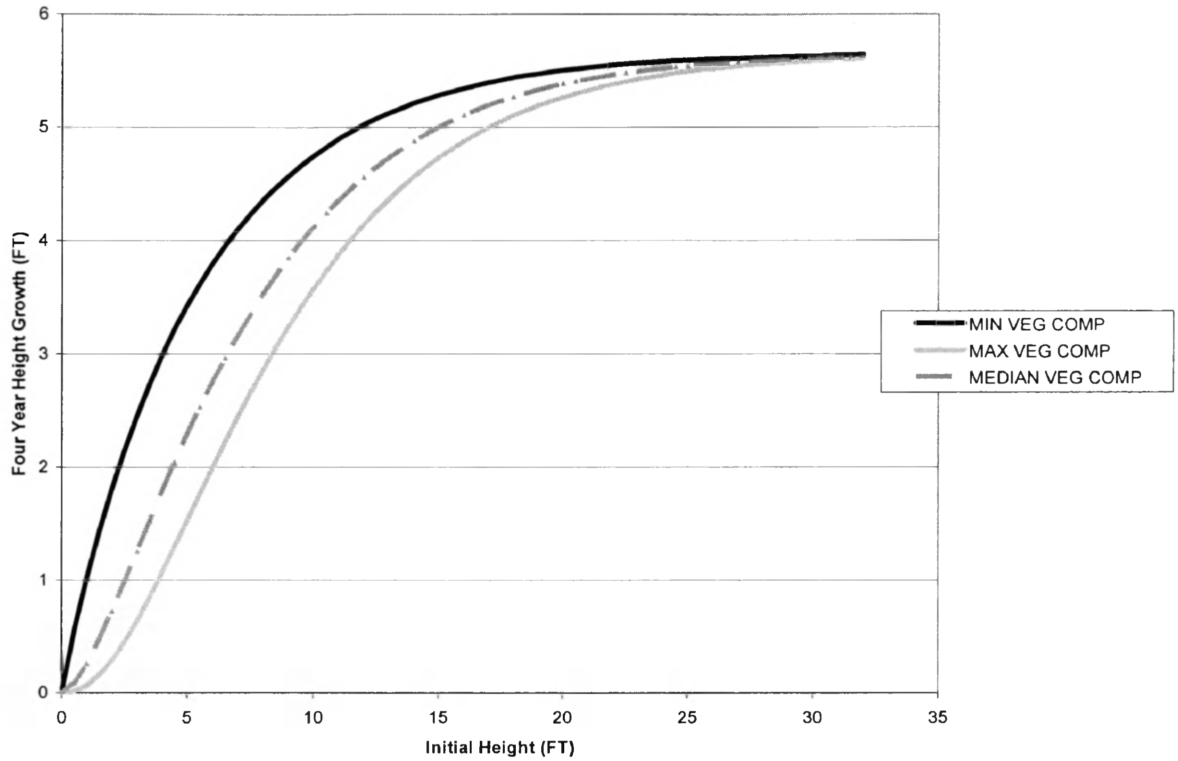


Figure 12. Ponderosa Pine Non-Linear Model Surface
(showing effects of vegetation competition)

Mean Site Index= 64 and Mean Total Tree to Tree Competition = 900%



As one can see, tree competition has a greater effect on height growth of small ponderosa pine than that of competition due to vegetation, although both are statistically significant.

Figure 13. Plot of Residuals versus Predicted Values for Non-linear Ponderosa Pine Model

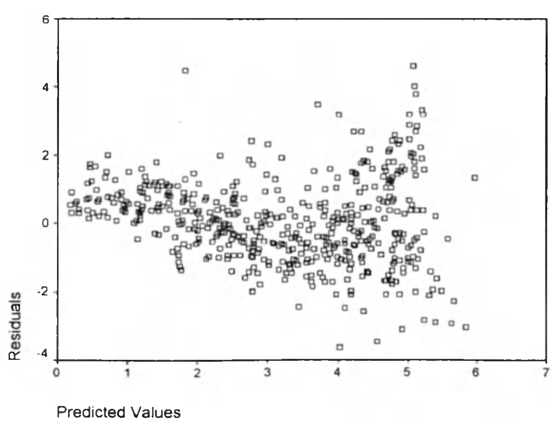
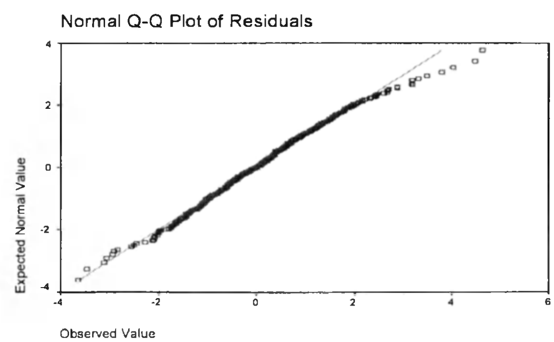


Figure 14. Normal Quartile Plot for Non-linear Ponderosa Pine Model



• *Douglas-fir*

Following the same procedure for Douglas-fir results in the following model as seen in Table 14 and Table 15.

Nonlinear Regression Summary Statistics Dependent Variable Four Year Height Growth

Table 14. Summary Statistics for Douglas-fir

Source	DF	Sum of Squares	Mean Square
Regression	**4**	**1596.30577**	**399.07644**
Residual	**180**	**315.91423**	**1.75508**
Uncorrected Total	**184**	**1912.22000**	
(Corrected Total)	**183**	**1073.67739**	

R squared = 1 - Residual SS / Corrected SS =   .70576

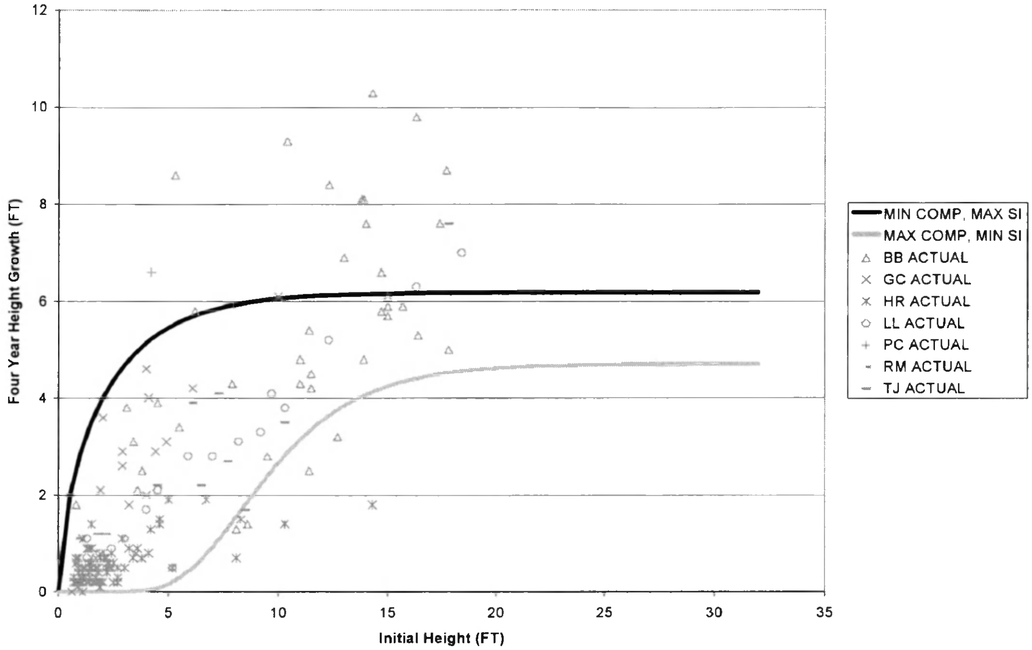
Asymptotic 95 %
Asymptotic Confidence Interval

Table 15. Coefficients of Non-Linear Regression for Douglas-fir

Parameter	Estimate	Std. Error	Lower	Upper
B1	**.087118562**	**.003681965**	**.079853194**	**.094383930**
B2	**.340702379**	**.043631911**	**.254606548**	**.426798210**
B3	**.006198871**	**.001258343**	**.003715869**	**.008681873**
B4	**.000029294**	**.000019857**	**-9.88872E-06**	**.000068477**

A graph showing the maximum and minimum height growth that this model can predict within the constraints of the collected data, along with the actual observed data by site is in Figure 15.

Figure 15. Maximum and Minimum Range of Non-Linear Model for Douglas-fir



The adjusted R square of this model is 0.706, with the coefficients behaving properly (Table 14 and Table 15). One Site, however, stands out as not being well described by the model, Big Bear (BB) (Figure 15). Figure 16 shows the graph displaying the effect of tree competition on height growth, with the site index set at the data sets mean of 60 feet and the vegetative competition set at the mean of 12,000 cubic feet per acre. Figure 17 is a graph displaying the effects of vegetative competition on height growth, with the same mean site index of 60 feet and the tree competition set at the mean of 650%.

Figure 16. Douglas-fir Non-Linear Model Surface
(showing effects of tree to tree competition)

Mean Site Index= 60 and Mean Vegetation Competition = 12,000 cubic feet per acre

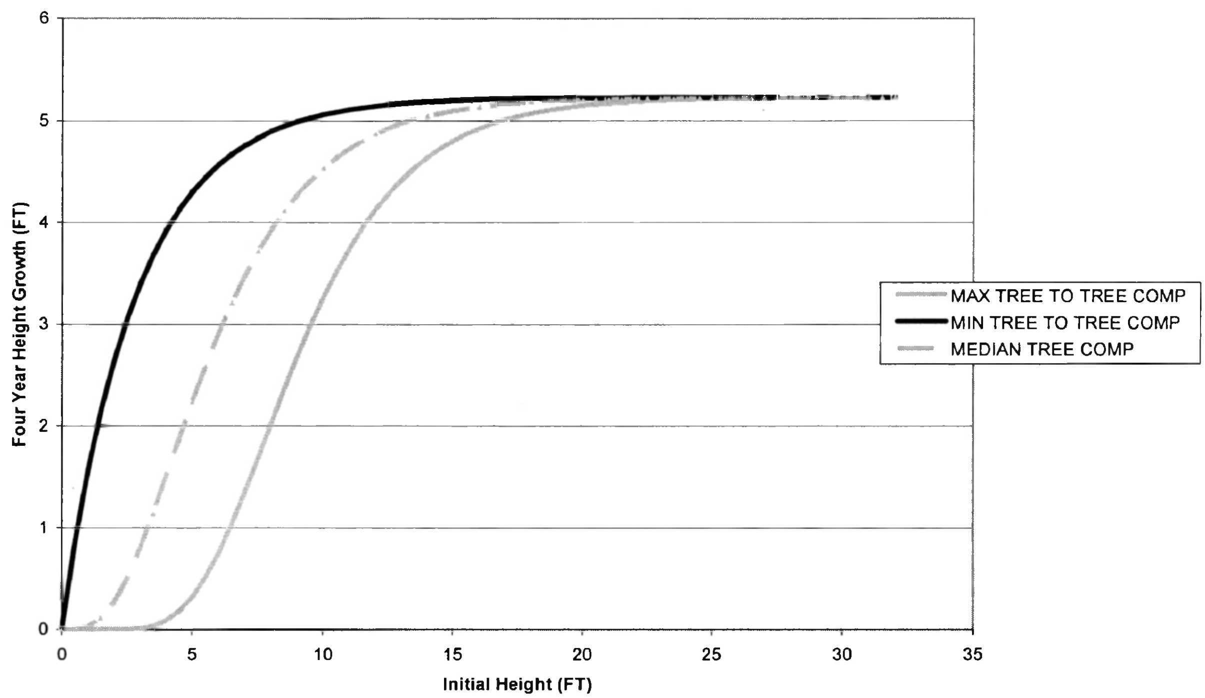
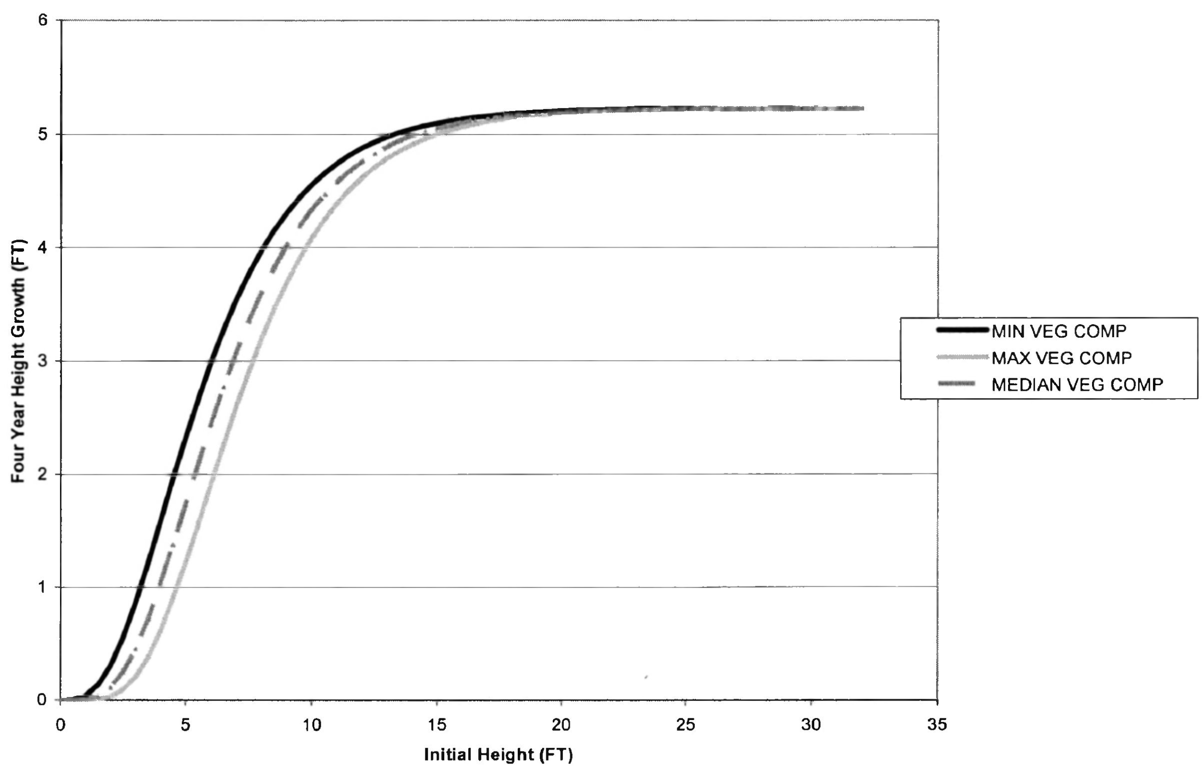


Figure 17. Douglas-fir Non-Linear Model Surface
(showing effects of vegetation competition)

Mean Site Index= 60 and Mean Tree to Tree Competition = 650%



As one can see, tree competition has a much greater effect on height growth of small Douglas-fir than that of competition due to vegetation and is statistically significant, while there is no evidence that vegetative competition is at all significant (Table 15).

Figure 18. Plot of Residuals versus Predicted Values for Non-linear Douglas-fir Model

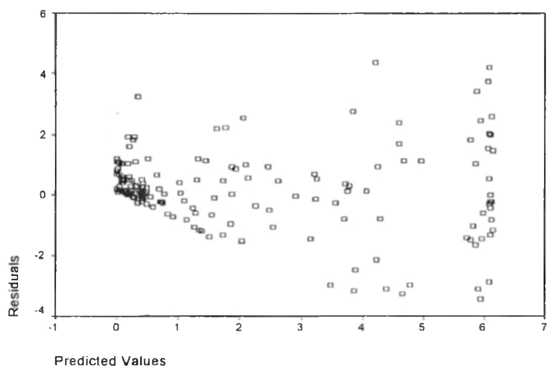
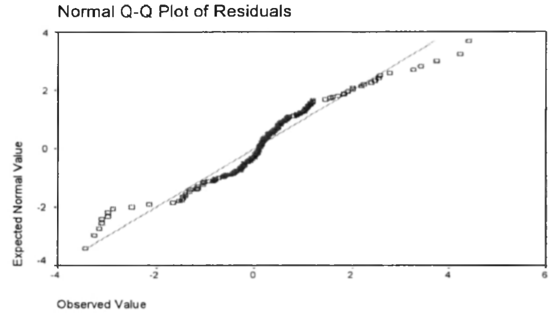


Figure 19. Normal Quartile Plot for Non-linear Douglas-fir Model



An attempt was made to explain more of the variation in height growth by adding a y-intercept to the equation. This analysis yielded a higher adjusted R square but the model then failed to adequately describe the data for either species for initial height of less then 5 feet tall. Another variation of the model attempted was to add one or all three of the interaction variables of site and competition to the exponent. None of these were statistically significant.

The two different approaches of analyzing these data yielded varying results. The log-linear regression approach and the attempt to address the question of the effects of competing vegetation on height growth were disappointing. For ponderosa pine, a few vegetation variables were significant but answered little to none of the variation in the model, with the best R-square of .539. The Douglas-fir model has an R-square of .625 yet no vegetation variables are significant. The R-squares for the non-linear regression models were similar, 0.506 for ponderosa pine and 0.706 for Douglas-fir.

The assumptions of homoscedasticity and that of normalcy seem to hold for both approaches with ponderosa pine, and there is no evidence to suggest otherwise with the Douglas-fir log-linear model, but obviously do not hold true for the Douglas-fir non-linear function (Figure 18 and Figure 19).

In analyzing the non-linear model behavior, two sites for ponderosa pine and one for Douglas-fir are not well described by the model. Investigation of these sites led to some troubling realizations. All three of these sites are centered in the middle of large clear cuts. On sites GC and PC site tree data was collected from the nearest fringe trees on the neighboring stands. At the BB site, site index was estimated from habitat type. Neither of these methods seems to have captured an accurate site index. Foresters familiar with these sites thought that PC has a site index of about 75 feet (it was calculated for this study to be 63 feet) and that of BB should be closer to 80-85 feet (estimated at 71 feet) (Patterson 2005). No educated guess of site index was available for GC. PC and BB were also planted with improved stock and sprayed for insects and disease early in the stand growth.

The tree-to-tree distance dependent variables are consistently significant. Competition from the overstory, as described in a spatial arena, obviously effects the height growth of the small trees, and the tree-to- tree competition is also important in explaining the variation in height growth, as are site index and initial height.
None of the transect based vegetation variables were significant and the significance of the meter square estimates is questionable in terms of height growth.

APPLICATIONS TO FOREST PROJECTION AND PLANNING SYSTEM

In order to proceed in the calibration/validation of FPS, one must gain an understanding of the simulator's small tree growth sub-routine.

Arney's model estimates, by region and species, the years it takes for an open grown, free-from-competition tree to reach twenty feet in height for each defined site class. He then adds estimated years onto this in proportion to the amounts of animal control, brush control, and site preparation that these trees will receive. This information is contained in FPS's Species Library.

Table 16 shows the original FPS Species Library and the library recalibrated to the INGY STCV data.

Table 16. FPS Species Library and INGY Re-Calibrated Library

		Site Index (m)			
		15		20	
		PP	DF	PP	DF
Idaho / Montana					
	FPS	**18**	**18**	**13**	**13**
	INGY	**32.2**	**33.8**	**19.3**	**15.8**
Inland Washington					
	FPS	**18**	**18**	**13**	**13**
	INGY	**25.4**	**No Data**	**18.8**	**18.1**

While the average deviation from FPS's library is about 5 years, it is far more pronounced in the lower site class, probably due to a lack of available INGY STCV data.

When graphed, the recalibrated data appears to trend similarly to the FPS data, as seen in Figure 20-Figure 23.

Figure 20. Years to Twenty Feet for Ponderosa Pine in Eastern Washington

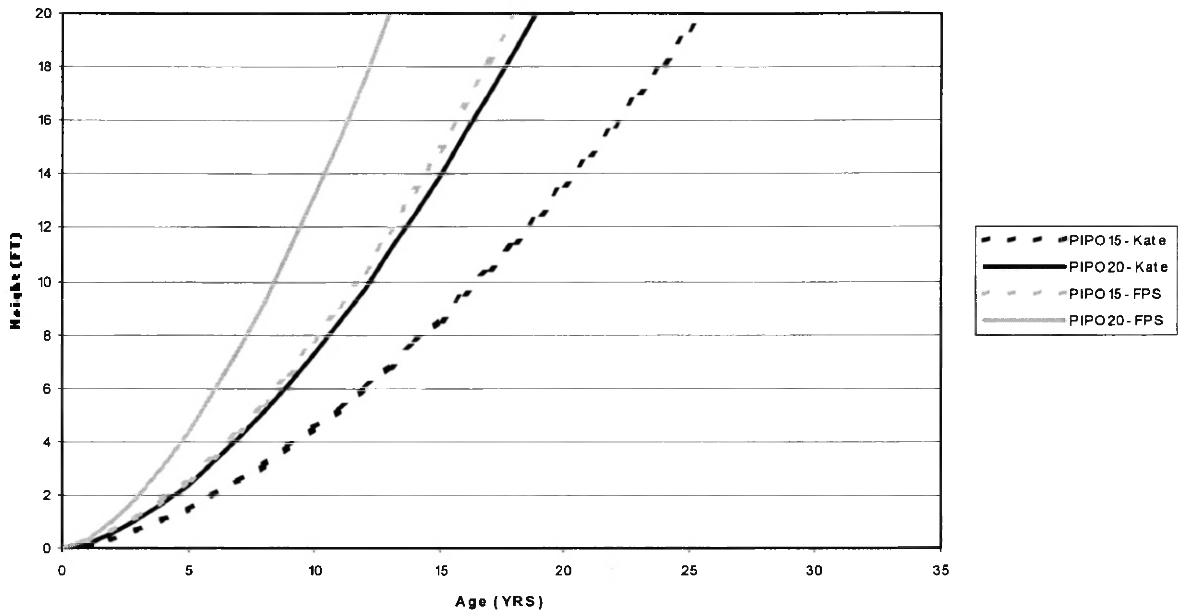


Figure 21. Years to Twenty Feet for Douglas-fir in Eastern Washington

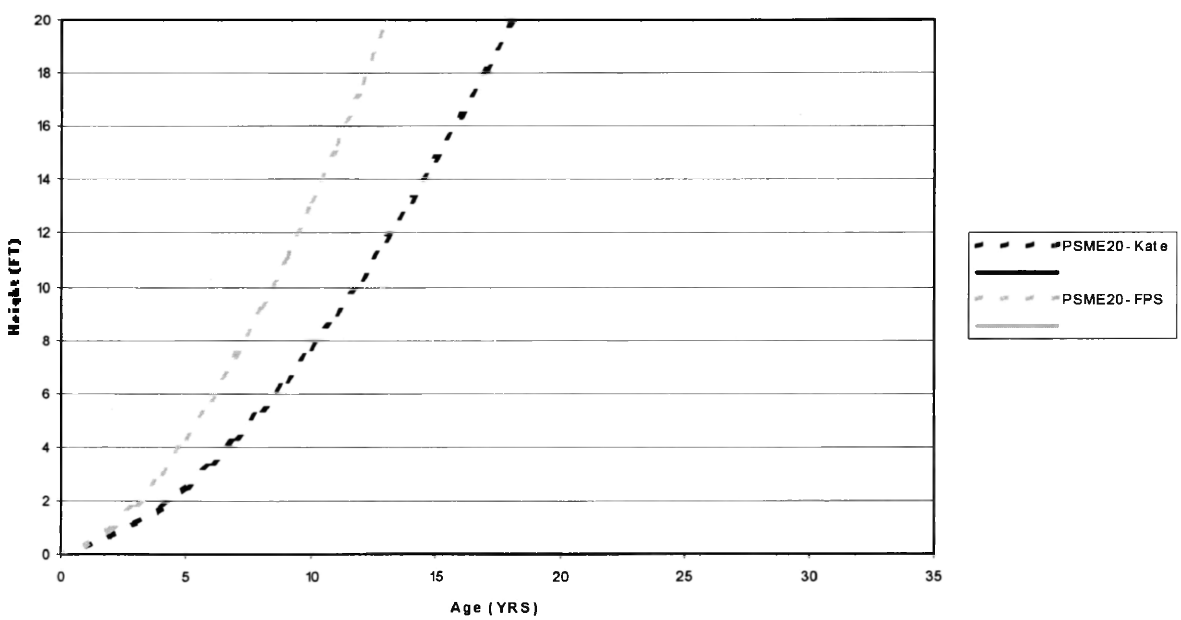


Figure 22. Years to Twenty Feet for Ponderosa Pine in Idaho/Montana

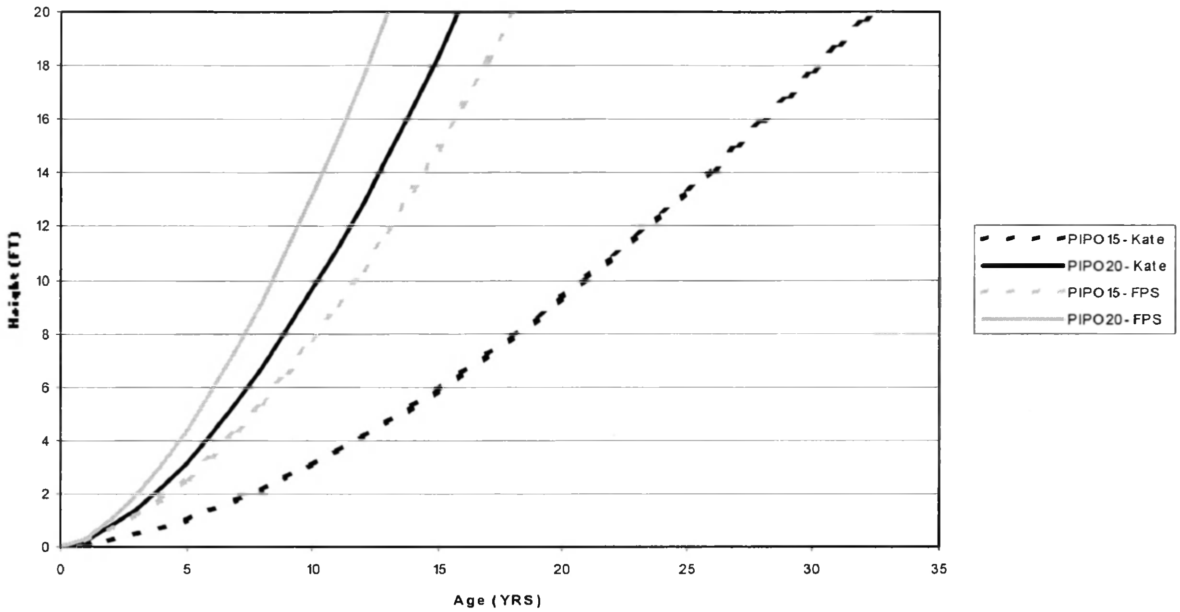
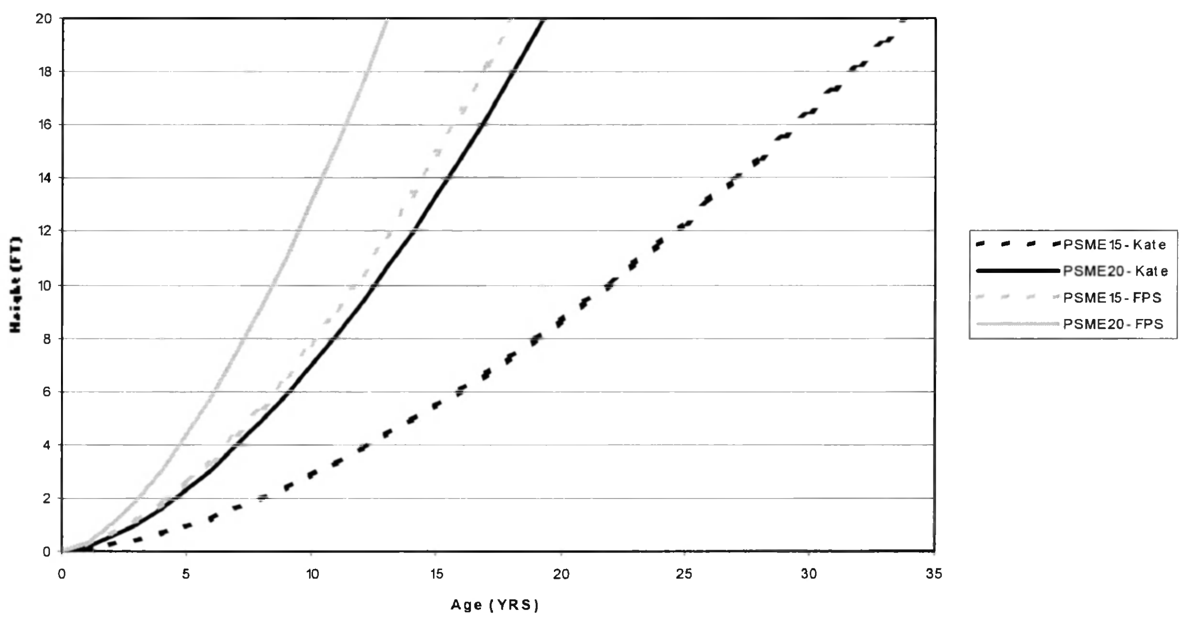


Figure 23. Years to Twenty Feet for Douglas-fir in Idaho/Montana



It would seem that the process of calibration was successful, and provided limited evidence of validation of the FPS parameters. There is not, however, enough INGY STCV data to have significant evidence to alter the FPS Species Library. Using this data in an attempt to validate and calibrate an existing simulator was quite successful. The results in this study parallel those contained in the FPS Library. Analysis of other larger data sets is required to positively calibrate such a complex model, with so many varying regions. Perhaps merging the INGY STCV data set with others already collected would create a large enough sample size to justify the calibration.

CONCLUSIONS AND RECOMMENDATIONS:

From this study it appears that a reduction in non-tree competing vegetation results in an increase in photosynthesis immediately, leading to an increase in diameter growth after two or three years and finally starting to show an increase in height growth after four years.

More analysis is needed to define "truth" as far as the vegetation variables are concerned. As for the objective of the INGY STCV study which was to model non-tree vegetation growth, this analysis is a necessary preliminary step. Another aspect not addressed in this study is the seasonality of vegetation measurements. Measurement timing of either post or pre- full expression of vegetation growth has an extremely large effect upon the modeling process and is probably the cause of a great deal of the noise in this analysis.

These analyses suggest that for the prediction of any growth, height, diameter or volume, in small trees, the tree centered measurements of vegetation are most influential in accounting for the variation in four-year height growth. The current measurements are also necessary to aid in the STCV objective modeling vegetation growth.

Four years may also not be enough of a response time to see significant results in height growth. Obviously, more time is needed before any changes in sampling design should even be considered, other than adding the tree-centered measurements of vegetation.

Another area to investigate is the accuracy of the site index measurements in these recently harvested units, perhaps by using pre-harvest estimates from the land owners would be helpful.

The INGY STCV data set is quite extensive. Only a small portion of the INGY STCV dataset was analyzed and the opportunities for further analyses and application would seem almost limitless.

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APPENDIX A:

Initial Height: The height of the growth node corresponding to time of initial treatment.

Ending Height: The height of the growth mode at the latest measurement available.

Initial Total Transect based Vegetation: Initial measurements are taken immediately pre-treatment and are the non-weighted sum of all initial transect based estimates.

Initial Transect based Shrub: Initial measurements are taken immediately pre-treatment. Calculations of these estimates are based on percent cover estimates that are derived from whether there is a hit or not on the five transect points falling within the STP. Percent cover of shrubs is then multiplied the average canopy depth at each point and expanded, resulting in cubic feet per acre estimates for each STP.

Initial Transect based Forb: Initial measurements are taken immediately pre-treatment. Calculations of these estimates are based on percent cover estimates that are derived from whether there is a hit or not on the five transect points falling within the STP. Percent cover of forbs is then multiplied the average canopy depth at each point and expanded, resulting in cubic feet per acre estimates for each STP.

Initial Transect based Grasses: Initial measurements are taken immediately pre-treatment. Average percent covers are calculated for each 36 square inches on the five points that fall within the STP. Average blade height is then multiplied by the percent cover and expanded, resulting in cubic feet per acre estimates.

Initial Meter Square based Total Vegetation: Initial measurements are taken immediately pre-treatment and are the non-weighted sum of all initial meter square based estimates.

Initial Meter Square based Grasses: Initial measurements are taken immediately pre-treatment. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of grasses, and expanded. This results in cubic feet per acre estimates.

Initial Meter Square based Forb: Initial measurements are taken immediately pre-treatment. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of forbs, and expanded. This results in cubic feet per acre estimates.

Initial Meter Square based Shrubs: Initial measurements are taken immediately pre-treatment. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of shrubs, and expanded. This results in cubic feet per acre estimates.

First Total Transect based Vegetation: First measurements are the earliest recorded post-treatment measurement and are the non-weighted sum of all first transect based estimates.

First Transect based Shrub: First measurements are the earliest recorded post-treatment measurements. Calculations of these estimates are based on percent cover estimates that are derived from whether there is a hit or not on the five transect points falling within the STP. Percent covers of shrubs are then multiplied the average canopy depth at each point and expanded, resulting in cubic feet per acre estimates for each STP.

First Transect based Forb: First measurements are the earliest recorded post-treatment measurements. Calculations of these estimates are based on percent cover estimates that are derived from whether there is a hit or not on the five transect points falling within the STP. Percent covers of forbs are then multiplied the average canopy depth at each point and expanded, resulting in cubic feet per acre estimates for each STP.

First Transect based Grasses: First measurements are the earliest recorded post-treatment measurements. Average percent covers are calculated for each 36 square inches on the five points that fall within the STP. Average blade height is then multiplied by the percent cover and expanded, resulting in cubic feet per acre estimates.

First Meter Square based Total Vegetation: First measurements are the earliest recorded post-treatment measurements, and these are the non-weighted sum of all first meter square based estimates.

First Meter Square based Grasses: First measurements are the earliest recorded post-treatment measurements. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of grasses, and expanded. This results in cubic feet per acre estimates.

First Meter Square based Forb: First measurements are the earliest recorded post-treatment measurements. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of forbs, and expanded. This results in cubic feet per acre estimates.

First Meter Square based Shrubs: First measurements are the earliest recorded post-treatment measurements. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of shrubs, and expanded. This results in cubic feet per acre estimates.

Ending Total Transect based Vegetation: Ending measurements are taken at the end of the four-year height growth period, and they are the non-weighted sum of all ending transect based estimates.

Ending Transect based Shrub: Ending measurements are taken at the end of the four-year height growth period. Calculations of these estimates are based on percent cover estimates that are derived from whether there is a hit or not on the five transect points falling within the STP. Percent covers of shrubs are then multiplied the average canopy depth at each point and expanded, resulting in cubic feet per acre estimates for each STP.

Ending Transect based Forb: Ending measurements are taken at the end of the four-year height growth period. Calculations of these estimates are based on percent cover estimates that are derived from whether there is a hit or not on the five transect points falling within the STP. Percent covers of forbs are then multiplied the average canopy depth at each point and expanded, resulting in cubic feet per acre estimates for each STP.

Ending Transect based Grasses: Ending measurements are taken at the end of the four-year height growth period. Average percent covers are calculated for each 36 square inches on the five points that fall within the STP. Average blade height is then multiplied by the percent cover and expanded, resulting in cubic feet per acre estimates.

Ending Meter Square based Total Vegetation: Ending measurements are taken at the end of the four-year height growth period, and these are the non-weighted sum of all ending meter square estimates.

Ending Meter Square based Grasses: Ending measurements are taken at the end of the four-year height growth period. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of grasses, and expanded. This results in cubic feet per acre estimates.

Ending Meter Square based Forb; Ending measurements are taken at the end of the four-year height growth period. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of forbs, and expanded. This results in cubic feet per acre estimates.

Ending Meter Square based Shrubs: Ending measurements are taken at the end of the four-year height growth period. Percent cover of a square meter is ocularly estimated and then multiplied by canopy depth of shrubs, and expanded. This results in cubic feet per acre estimates.

CSI understory: All tagged subject trees are stemmed mapped and the distances between them calculated. Using Arney's (1995) equation of open grown crown widths, $(CRWID = 4.02 + (2.12(DBH)) - (0.02(DBH^2)))$, the overlap areas are then calculated, summed, and divided by the subject trees open grown crown area. This results in a variable that compares all tagged tree to tagged tree competition in the understory and is no less than 100.

CSI overstory: The same process is followed in the creation of this variable as in CSI understory except that each subject tree is compared only to the overstory trees in the vicinity, and never to itself. This results in a variable with a minimum of 0.

CCF understory: Implementation of the tallied trees is necessary in this variable's calculation. Since all tagged trees are included in the tally, and effort has been made to remove all tagged trees whose influence has already been accounted for in CSI understory. A regression, by species and by site, of the relationship between the mean height of the two foot height classes and a DBH was then calculated. These mean DBHs were then used to create the open grown crown areas for each size class, summed, and divided by the square footage of the STP.

Total Tree Competition: The addition of the three previous defined tree competition variables, CSI understory, CSI overstory, and CCF understory.

Site Index: The height in feet of an open grown, free from competition tree at a particular index age (age 50 in the INGY study).

APPENDIX B:

Steps to calibrate the FPS small tree growth model:

1. Manipulate current data set so that each record contains:
    a. Initial Height
    b. Ending Height
    c. Species
    d. Site Index
    e. Difference in years from initial to ending height
    f. Remove all trees with severe damage
    g. Remove all trees with an initial height greater than twenty feet

2. Begin an iterative process with a step of 0.1 of the following
    a. Age_20 = 0
    b. Age_20 = Age_20 + .1
    c. Age = Age_20 * (Initial Height/ 20)^.625
    d. Age = Age + years between measurements
    e. Calculated Height = 20 * (Age/Age_20)^1.6
    f. If the calculated height is greater than the ending height then recalculate from step 2 until they are equal.

3. Calculate means by species, region, and site class.