

**Evaluating the Small Tree Height Growth Component of
Prognosis^{BC} for the IDF dk1, dk2, and dk3 Subzone Variants**

**A Report to the
Forest Practices and Research Branches
B.C. Ministry of Forests**

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-by-

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Index

Index.....	ii
List of Tables.....	iii
List of Figures	iii
1.0 Introduction	1
2.0 Background on Small Tree Height Growth.....	3
2.1 Factors Influencing Early Height Growth.....	3
2.2 Modelling Early Height Growth	5
2.3 The Prognosis ^{BC} Small Tree Height Growth.....	7
3.0 Methodology and Preliminary Data Interpretation	8
3.1 Field Methods.....	8
3.1.1 Sampling Frame	8
3.1.2 Sampling Procedures.....	8
3.2 Data Processing	9
3.3 Variables used for Modelling Small Tree Height Growth	9
3.3.1 Measured Attributes	9
3.3.1.1 Individual Tree Variables.....	10
3.3.1.2 Ecological variables.....	12
3.3.1.3 Topographic Variables.....	12
3.3.1.4 Years since disturbance.....	16
3.3.2 Derived Attributes	18
3.3.2.1 Individual Tree Attributes	18
3.3.2.2 Stand Density Attributes.....	18
3.3.2.3 Stand Structure Attributes	26
3.3.2.4 Site Index.....	31
3.4 Models for Predicting Five-Year Small Tree Height Growth.....	33
4.0 Results	34
5.0 Summary	39
6.0 References	40
Appendix I – Model Coefficients.....	44

List of Tables

Table 1. Major forest management considerations (BC Ministry of Forests 1999).....	1
Table 2. Summary of the final five-year height growth equations.....	34
Table 3. Fit statistics for equations used for predicting small tree five-year height growth.....	34

List of Figures

Figure 1. Height growth vs. total height for Douglas-fir.	11
Figure 2. Height growth vs. total height for lodgepole pine.	11
Figure 3. Height growth vs. total height for spruce.	11
Figure 4. Five-year height growth vs. percent cover of herbs for Douglas-fir	13
Figure 5. Five-year height growth vs. percent shrub cover for douglas-fir.	13
Figure 6. Five-year height growth vs. percent cover of herbs for lodgepole pine.	13
Figure 7. Five-year height growth vs. percent shrub cover for lodgepole pine.	14
Figure 8. Five-year height growth vs. percent herb cover for spruce.	14
Figure 9. Five-year height growth vs. percent shrub cover for spruce.....	14
Figure 10. Five-year height growth vs. slope for Douglas-fir.....	15
Figure 11. Five-year height growth vs, elevation for Douglas-fir	15
Figure 12. Five-year height growth vs. elevation for lodgepole pine.	16
Figure 13. Five-year height growth vs. elevation for spruce	16
Figure 14. Five-year height growth vs. years since disturbance for Douglas-fir.....	17
Figure 15. Five-year height growth vs. years since disturbance for lodgepole pine.....	17
Figure 16. Five-year height growth vs. years since disturbance for spruce.....	17
Figure 17. Five-year height growth vs. height/diameter ratio for Douglas-fir.....	19
Figure 18. Five-year height growth vs. height/diameter ratio for lodgepole pine.	19
Figure 19. Five-year height growth vs. height/diameter ratio for spruce.....	19
Figure 20. Five-year height growth vs. TPH for Douglas-fir.....	20
Figure 21. Five-year height growth vs. TPH for lodgepole pine.	20
Figure 22. Five-year height growth vs. TPH for spruce.....	20
Figure 23. Five-year height growth vs. BA/HA for Douglas-fir.....	21
Figure 24. Five-year height growth vs. BA/HA for lodgepole pine.	21
Figure 25. Five-year height growth vs. BA/HA for spruce.....	21
Figure 26. Five-year height growth vs. BAL for Douglas-fir.	22
Figure 27. Five-year height growth vs. BAL for lodgepole pine.	22
Figure 28. Five-year height growth vs. BAL for spruce	22
Figure 29. Five-year height growth vs. CCF for Douglas-fir.....	23
Figure 30. Five-year height growth vs. CCF for lodgepole pine.	23
Figure 31. Five-year height growth vs. CCF for spruce.....	23
Figure 32. Five-year height growth vs. QMD for Douglas-fir.....	24
Figure 33. Five-year height growth vs. QMD for lodgepole pine.....	24
Figure 34. Five-year height growth vs. QMD for spruce.	25
Figure 35. Five-year height growth vs. RD for Douglas-fir.....	25

Figure 36. Five-year height growth vs. RD for lodgepole pine.	26
Figure 37. Five-year height growth vs. RD for spruce.....	26
Figure 38. Five-year height growth vs. SDI for Douglas-fir.....	27
Figure 39. Five-year height growth vs. SDI for lodgepole pine.	27
Figure 40. Five-year height growth vs. SDI for spruce.....	27
Figure 41. Five-year height growth versus q for Douglas-fir.	28
Figure 42. Five-year height growth vs. q for lodgepole pine.....	28
Figure 43. Five-year height growth vs. q for spruce	28
Figure 44. Five-year height growth vs. Shannon’s index for Douglas-fir.	29
Figure 45. Five-year height growth vs. Shannon’s Index for lodgepole pine.....	29
Figure 46. Five-year height growth vs. Shannon’s Index for spruce.	30
Figure 47. Five-year height growth vs. STVI for Douglas-fir.	30
Figure 48. Five-year height growth vs. STVI for lodgepole pine.....	31
Figure 49. Five-year height growth vs. STVI for spruce.	31
Figure 50. Five-year height growth vs. SI for Douglas-fir.....	32
Figure 51. Five-year height growth vs. SI for lodgepole pine.	32
Figure 52. Five-year height growth vs. SI for spruce.....	32
Figure 53. Plot of residuals from model M-1 for Douglas-fir.....	35
Figure 54. Plot of residuals from model M-1 for lodgepole pine.	35
Figure 55. Plot of residuals from model M-1 for spruce.....	36
Figure 56. Plot of residuals from model M-2 for Douglas-fir.....	36
Figure 57. Plot of residuals from model M-2 for lodgepole pine.	37
Figure 58. Plot of residuals from model M-2 for spruce.....	37
Figure 59. Plot of residuals from model M-3 for Douglas-fir.....	37
Figure 60. Plot of residuals from model M-3 for lodgepole pine.	38
Figure 61. Plot of residuals from Model M-3 for spruce.	38

1.0 Introduction

The key to successful timber management is proper understanding of growth processes. One of the objectives of modelling forest development is to provide tools that enable foresters to compare alternative silvicultural treatments. Growth modelling is also necessary for evaluating the consequences of a particular management action on the future development of a forest.

The specific management objectives that are pursued by forest managers depend on the structure of a stand and the management objectives for the forest as a whole. The level of resolution of the forecast required to support these objectives determines the most appropriate modelling technique.

In British Columbia, many of the growth and yield and timber supply analysis systems evolved to address stand structures resulting from clearcutting or some other form of stand replacing disturbance. The use of clearcutting has been rapidly decreasing over the past decade (J.S. Thrower and Assoc. 1995) and has been replaced by various forms of partial cutting. Partial cutting appears to be an attractive alternative to clearcutting for some species and geographic regions in the Province (Nelson Forest Region, Cariboo Forest region, Kamloops Forest Region - J.S. Thrower and Assoc. Ltd. 1995).

As an example, the major objectives, issues, and considerations for the Kamloops Timber Supply Area are listed in the table below (BC Ministry of Forests 1999a). In order to achieve most of these objectives, partial cutting is required.

Table 1. Major forest management considerations (BC Ministry of Forests 1999a)

Consideration/issue	Description
Visual quality objectives (VQO)	Visually sensitive areas with objectives of preservation, retention, partial retention and modification visual quality.
Community watersheds	Community watersheds as defined in the <i>Forest Practices Code Act</i> and mapped by the Ministry of Environment, Lands and Parks (MELP), Water Management Branch.
Stand-level biodiversity	Requirements for retaining wildlife trees and wildlife tree patches.
Landscape-level biodiversity	Kamloops Land and Resource Management Plan (LRMP) requirements for interim biodiversity emphases.
Riparian requirements	Forest practices code requirements and Kamloops LRMP requirements for streamside reserve and management zones.
Caribou habitat resource management zone (RMZ)	Kamloops LRMP approved caribou habitat resource management zone, including early winter, late winter, corridors and a moratorium area.
Critical deer winter range	Kamloops LRMP approved critical deer winter range.
Protected areas (PA) and protection resource management zones	Several new parks and protection RMZs approved through the Kamloops LRMP.

The BC Ministry of Forests has adapted the Prognosis model, originally developed for the northern intermountain region of the United States (Stage 1973, Wykoff *et al.* 1982), to assist in predicting the future development of partially cut stands in the central and southeastern regions of the province. Specific components of the B.C. version of this model (Prognosis^{BC}) have been tested for a range of conditions and modified when necessary.

Previous work determined that the original Prognosis small tree height growth component included in Prognosis^{BC} did not perform adequately for the Interior Douglas Fir dry cool subzone variants 1, 2, and 3 (IDFdk1, dk2, and dk3, respectively) (Lencar and Marshall 2000). This report describes the work done to calibrate/modify the small tree height growth submodel of Prognosis^{BC} for these subzone variants and outlines future steps and approaches to improve the small tree height growth component.

2.0 Background on Small Tree Height Growth

Growth results from the interaction of two opposing forces. The active component, mostly manifested in the expansion of an organism, represents the innate tendency toward exponential multiplication. This component is associated with biotic potential, photosynthetic activity, absorption of nutrients, and anabolism. The opposing component represents the restraints imposed by external (competition, limited resources, stress) and internal (ageing, self-regulatory mechanisms) factors. These factors have been referred to as environmental resistance, respiration, and catabolism.

These two components are reflected in two pairs of laws reflecting both the multiplicative and limiting components of growth. Hutchinson's (1978) two postulates of population growth were: (1) every living organism has arisen from at least one parent of like kind (the postulate of parenthood); and (2) in a finite space, there is an upper limit to the number of finite beings that can occupy or utilise the space under consideration (the postulate of an upper limit). Medawar and Medawar (1983) stated: (1) fundamentally, growth is multiplicative; that which results from biological growth is itself, typically, capable of growing; and (2) the relative growth rate is always decreasing (Minot's law).

The conflict between infinity that is implicit in multiplicative reproduction and the limit imposed by finite space is the chief source of all change in living beings, including growth. Growth equations provide a succinct expression of this conflict and its resolution.

2.1 Factors Influencing Early Height Growth

Tree height generally follows a sigmoidal curve with age, when the tree is growing in full sunlight. Height growth is slow at the beginning, when the tree is too small to accumulate energy for rapid terminal growth. With an increase in size, an increased flow of energy is available for the terminal shoot, causing a rapid increase in height. Eventually, the growth rate slows as increased stresses determined by different factors limit the extension of the terminal shoot (Oliver and Larson 1996).

Many factors contribute and interact to define the height growth of individual trees (Oliver and Larson 1996). The characteristic height growth pattern varies with species (Carmean 1970). The genetic attributes of a species define the adaptive capabilities of that species, including its height growth potential. However, the growth patterns of understory trees can vary drastically within a species.

The height growth of understory trees can show cyclical patterns, varying from high to low rates, as the trees are periodically released by temporary overstory gaps. The results of a study in uneven-aged interior Douglas-fir in the Merrit Timber Supply Area showed that height development of the sampled trees encompassed periods of both suppression and release (J.S. Thrower and Assoc. Ltd. 1997). During periods of unsuppressed growth, small trees, previously suppressed, can grow at rates equal to the height growth of dominant trees which were never

suppressed on the same site (Oliver and Larson 1996). Many tree species, like interior Douglas-fir, demonstrate the ability to resist suppression and increase height growth after release (Krauch 1956).

Within the intrinsic potential of a species, height growth is mostly influenced by site quality, which reflects the sum of the available resources at a given location. The time required for a species to achieve a given height varies with site (Oliver and Larson 1996). Generally, height growth culminates sooner on better sites, and then declines more rapidly after reaching the point of culmination compared to poorer sites (Kramer 1988). Tree height growth is relatively independent of the degree of crowding and amount of foliage because photosynthate allocation to height growth is given priority over diameter growth.

The site potential and a species' inherent characteristics provide the framework for individual tree development. Because forests are collectives of trees, which are expressing different stages of development, an entire array of conditions and interactions may manifest. These conditions and interactions produce a variety of height growth patterns and make it difficult to attribute height differences specifically to site quality, competition, genetics, age, stand structure or development stage, or other factors.

The 'relay floristic' pattern of establishment, when one species invades after another (Oliver and Larson 1996), is considered to be the driving factor behind the height stratification of northern hardwoods, rather than differences between or within species' height growth rates (Palik and Pregitzer 1991, in Cobb *et al.* 1993). Under this assumption, time of establishment is one of the main factors influencing competitive advantage. The first species to establish monopolise resources and have a competitive advantage over later established species. However, differences among species in their pattern of growth also reflect an "initial floristic" pattern of establishment that assumes most plants existing in a stand invade shortly after a disturbance (Oliver and Larson 1996). Pioneer species, which are usually shade intolerant, tend to have asymptotic height growth; shade tolerant species generally show mostly slow linear growth patterns; semi-tolerant species tend to have sigmoidal growth patterns (Oliver and Larson 1996).

Stand structure varies over time as a result of changes in tree dimensions, regeneration, and mortality. These changes alter the growing environment, which, in turn, influences stand dynamics in a feedback loop. Under any of the regeneration establishment patterns described above, the species first established or the species that initially dominate the stand, will not necessarily be dominant later in the stand development.

Differences among species in height growth, combined with the level of shade tolerance of a species, affect stratification of the species into layers (Cameron 1996). Crown position in the forest canopy was found to be an important factor in the growth rate achieved by individual trees (Oliver and Larson 1996). Also, the differences in height growth development between species within a growing season may favour those species with height growth during a period of time when the growing conditions are more favourable (Schmidt *et al.* 1980).

The combination of species present has also been found to influence height growth. Certain species can compete more effectively in some species combinations than in others (Cobb 1993).

LePage (1993) attributed different growth rates for certain species to the effects of the surrounding species. This influence may be positive (Kneeshaw and Bergeron 1996).

The height growth patterns for a species also vary with tree vigour. Wahlenberg (1946) found that longleaf pine (*Pinus palustris*) seedlings remain in a grass stage with stagnant height growth for up to 20 years. When vigorous enough, they pass out the grass stage and grow rapidly in height. Shade-tolerant species may be better able to reduce their height growth in shade than shade-intolerant species, and this might be seen as an adaptation to survive in shady conditions (Beaudet and Messier 1998). Hence, the usefulness of height growth as an indicator of vigour will vary with a species' tolerance to shade. Nevertheless, Parent and Messier (1995) suggested that absolute height growth could constitute a good indicator for shade-tolerant balsam fir (*Abies balsamea*) while Murphy *et al.* (1999) found that it could be useful for shade intolerant lodgepole pine (*Pinus contorta*).

Yearly climatic fluctuations can also impact on height growth. During some years, Pacific silver fir (*Abies amabilis*) saplings grew less than 5 cm compared with 30 cm in a normal year, apparently because of environmental influences (Crawford *et al.* 1982).

Height growth of some young Douglas-fir (*Pseudotsuga menziesii*) plantations in western Washington have exceeded expectations where weed competition has been controlled and vigorous seedlings planted (Oliver and Larson 1996). The importance of competing vegetation was found to be significant in a study in the southern Appalachians, where the height distribution of major regenerating species were skewed away from small height classes when understory vegetation was high (Clinton *et al.* 1994).

Height growth of Douglas-fir has been found to increase quickly when released from overstory competition. In California, height growth response occurred two to four years after release; trees that grew the fastest prior to release responded the quickest. Three factors were found to be important in predicting post-release height growth: (1) the pre-release height growth; (2) live crown ratio at the time of release; and (3) whether the five-year pre-release annual height growth was decelerating, constant, or accelerating (Helms and Standiford 1985). In southwest Oregon, Douglas-fir advance regeneration responded well even after 50 years of suppression. Trees developed large crowns for the first three years after release and then began to increase in height growth (Weber and Tesch 1985).

2.2 Modelling Early Height Growth

Early height growth seems to follow a fast or a slow linear model. Both these models are in accordance with any of the biologically explicit equations described by Zeide (1996). He describes all of the non-linear equations presented as being biologically explicit, because they have similar constraints to an individual/population growth rate in a finite space. Froese (2000) provided a review of juvenile height growth modelling in which all the examples provided used age as a basic predictor included in certain non-linear functions.

Most of the equations described by Zeide (1996) use age as the main predictor variable, which is not very suitable for predicting small tree height growth. However, Zeide did present an equation (the Y-decline form) which contained only tree size as an independent variable, and which was an equally good predictor as those equations which included the age of the tree as independent variable. The Y-decline form can be expressed as:

$$\ln(y') = k + p\ln(y) + qy \text{ or } y' = k_1 y^p e^{qy} \quad [1]$$

where y is the tree size variable (height, diameter, volume); y' is the differential form of y (i.e., the increment dy/dt); k is the intercept term; p is the size constant; and q is the age constant.

The above equation was described as a Type II combined exponential and power function, and was used by Thompson (1996) to develop a model for lodgepole pine (*Pinus contorta*) in the Nelson Forest Region. A slightly different function, described as a Type I combined exponential and power function, was used by Nigh and Love (1999) for estimating the juvenile height of lodgepole pine in the Prince Rupert Forest Region. They also used age as the main predictor variable. Froese (2000) used a power function or a combined exponential and power function for predicting height, with age and certain site variables as independent variables.

McCaughey and Schmidt (1982) used linear regression models to predict understory tree release following harvest cutting in spruce-fir forests of the U.S. Intermountain West. The best predictors were initial height, post-treatment basal area, pre-harvest height growth, and initial crown length. The coefficients of determination (R^2) ranged between 0.11 and 0.58 as a function of species and location. Their models were empirical and thus lacked theoretical causality between the dependant variable and the predictors.

Monserud and Ek (1977) argued that tree size rather than age is the relevant variable for determining when an understory tree reaches overstory status. They developed a model for predicting height growth using height classes. They assumed that trees in each height class were evenly distributed throughout the class, and grew at the same rate. Essentially, only height increments need be determined in order to arrive at new height-class structure for surviving trees. This growth rate was approximated by the growth rate of the midpoint tree in each height class. The movement of stems to larger height classes was based on potential height growth derived from site index curves modified by a competition index sensitive to the overstory tree spatial pattern.

Boisvenue (1999) separated tree species into shade tolerance classes in her attempt to calibrate small tree height growth for the ICHmw2 subzone variant in the vicinity of Nelson, B.C. The base model used was the Prognosis NI sub-model for predicting small tree height growth in which she also included the age of the trees. The R^2 and I^2 values ranged from 0.35 to 0.88 for different groups of species.

2.3 The Prognosis^{BC} Small Tree Height Growth Sub-Model

Prognosis^{BC} is an increment model that can incorporate observed growth into projections over successive time steps (commonly 10 years), eliminating the need to know the age of the stand. The growth of seedlings and saplings with DBH < 7.5 cm is localized using periodic height increments (5 years).

The Prognosis equation for predicting small tree height growth is (Wykoff 1986):

$$\begin{aligned} \text{LN}(\text{HTG}) = & \text{HAB} + \text{LOC} + 0.22157 \times \text{SL} \times \cos(\text{ASP}) - 0.12432 \times \text{SL} \times \sin(\text{ASP}) \\ & - 0.10987 \times \text{SL} + b_1 \times \ln(\text{HT}) + b_2 \times \text{CCF} + b_3 \times (\text{BAL}/100) \end{aligned} \quad [2]$$

where HTG is the height increment predictions for small trees, HAB is a constant that is dependent on habitat type, LOC is a constant that is dependent on location, ASP is stand aspect (degrees), SL is stand slope ratio (/100), HT is tree height, CCF is crown competition factor, BAL is the basal area in larger trees, and b_1 , b_2 , b_3 are species-specific regression coefficients.

This equation is similar to the Y-decline form equation described by Zeide (1996) and does not include the age of a tree.

3.0 Methodology and Preliminary Data Interpretation

3.1 Field Methods

Data were collected during the summer of 1999. The sampling and measurement protocols were based on the methods used for collecting data for the initial development of the small tree and regeneration component models in Prognosis (Ferguson and Crookston 1991), previous experience, and consultation with local foresters.

3.1.1 Sampling Frame

The IDFdk1, dk2 and dk3 are not randomly distributed across the landscape, but are a function of climatic, edaphic, ecological, and topographic factors. Harvesting locations were assigned so as to minimize costs of access and to maximize financial returns; therefore, these sites are not randomly distributed either.

This project focused on areas in the IDF dk1, dk2, and dk3 that were partially harvested in the last 20 years. To have unbiased estimates of this population that is not randomly distributed, randomness needs to be introduced through the sampling design.

For the IDF dk1 and dk2 subzone variants, the BC Ministry of Forests (BCMoF) provided the sampling frame for Kamloops Forest Region; it consisted of all polygons located in the IDFdk1 and dk2, irrespective of ownership, that were disturbed in the last 20 years. Stratified random sampling was conducted separating the polygons by year since disturbance (2 - 20) and intensity of disturbance (0 - 100%). Stands were randomly selected from each strata to ensure an unbiased choice among all candidates stands. Practical reasons (available time) did not allow sampling a large number of plots for each combination of factors. Stratification of the area into several smaller geographic areas was not done, since the geography and climate are very alike across the extent of IDF dk1 and dk2.

For IDF dk3, the Ministry of Forests and Inland Timber Management Ltd. (1999) constructed the sampling frame. Stratified random sampling was conducted by having polygons separated by year since disturbance into three strata: 1995 - present, 1990 - 1994 and pre - 1990. An attempt was made to establish an equal number of plots in the three strata.

3.1.2 Sampling Procedures

Stands (polygons) were selected from the frame described above for sampling. For IDF dk1 and IDF dk2 approximately 80 percent of the sampling effort was concentrated in these partially cut stands. The remaining 20 percent of the sample sites were split between undisturbed and clear-cut areas. These areas were selected purposively based on similarities in site characteristics to those in the partially cut stands. For IDF dk3, 90 percent of the sampled were located in partially cut stands, and the remaining 10 percent were located in clear-cut stands.

Sampling within sites and the data collection was slightly different in IDF dk1 and IDF dk2, than in IDF dk3. A detailed description of the sampling within sites and data collected is provided in Lencar and Marshall (2000).

The number of sites sampled was solely a function of time and budget. For IDF dk1, 120 plots were located on 40 sites; for IDF dk2, 62 plots on 21 sites were selected; for IDF dk3, 153 plots on 50 sites were selected.

3.2 Data Processing

All data were recorded at the plot on waterproof paper, and entered into Microsoft Excel electronic databases shortly thereafter. This process ensured that possible errors were identified promptly while checking discrepancies in the field could be done for little additional cost.

Data processing was performed using Microsoft Excel and SAS (version 6.12) running under Windows 98. The data collected were separated into large tree, small tree, and regeneration components. These files were subsequently manipulated to provide various summaries of the data. A detailed description of the measurements taken on each plot and summaries of the data are presented in Lencar and Marshall (2000).

3.3 Variables used for Modelling Small Tree Height Growth

Several variables and derived attributes were used to develop models for predicting small tree height growth. Most of the variables considered were similar to those used in the original Prognosis small tree height growth model because it was felt that these variables represented a reasonable set that could be measured in the field. Some new derived attributes were added with the idea that they might improve growth prediction. The predictor variables considered can be grouped as follows: measured attributes (individual trees variables, ecological and topographical variables, time related variables) and derived attributes (individual tree attributes, stand density attributes, stand structure attributes, and competitive indices).

3.3.1 Measured Attributes

Each plot was made as independent as possible by recording plot attributes (biogeoclimatic ecological classification [BEC] site series, slope, aspect, type of site preparation, topographic position, and residual overstory density by species). Each plot had to be homogeneous from a stand structure perspective. If, by chance, a plot ended up in a heterogeneous area (clearing and uncut stand), it was offset with 20 m in a randomly chosen direction. Systematically spacing the plots also helped maintain independence among plots within stands because plots were dispersed throughout the stand. The year of cutting, geographic location, elevation (with small variations) and sometimes intensity of disturbance were variables that did not differ among plots within a stand.

The trees on each plot were separated into two sub-populations: (1) large and small trees and (2) regeneration. These sub-populations describe the stand as a whole when combined. Regeneration was defined as all trees above 15 cm in height and below 7.5 cm dbh (Ferguson and Carlson 1993). Small trees were defined as all trees with a dbh between 2.0 cm and 7.5 cm. Large trees were defined as trees above 7.5 cm dbh (Stage and Alley 1972).

3.3.1.1 Individual Tree Variables

The following measurements and observations were made for each tree:

- 1) species
- 2) dbh: diameter of the tree stem, outside bark, at 1.3 m above ground on the uphill side. Measured using a calliper on small trees (less than 7.5 cm) and a diameter tape on larger trees. Dbh was recorded to the nearest 0.1 cm.
- 3) height: at least five small trees of each species and two large trees of each species were measured for total height. Height was measured using a height pole for shorter trees (less than 9 m) and a Vertex 2000 ultrasound hypsometer for taller trees. The measurements were recorded to the nearest cm for the shorter trees and to the nearest 0.1 m for the taller trees.
- 4) five-year height growth: at least five small trees for each species were measured for five-year height growth. These were the same trees measured for total height. The measurement was recorded to the nearest cm.
- 5) age: in a similar study performed to calibrate the PrognosisBC small tree height growth model for the ICHmw2 subzone variant in the vicinity of Nelson, Boisvenue (1999) found that the total age of the tree did not contribute significantly to predicting small tree height growth. Therefore, age of the small tree was not considered in this study. However, the measurements that were taken indicated that the ages of the understory trees were much higher than one would expect from trees generally under 6 m tall. A similar observation was made by McCaughey and Schmidt (1982) in a study on small tree height growth in Idaho, Wyoming and Utah.

Total height appears to be an important predictor variable in modelling small tree height growth. Initial growth response after release was found to be positively correlated with height at the time of release for white fir (*Abies alba*) (Tesch and Korpela 1993). Others have found that height growth of taller advance regeneration responded more slowly to release (McCaughey and Schmidt 1982, Paquin and Doucet 1992, Riopel 1999). These contradictory results may depend on the stage of height that is considered in a particular study, the growing conditions before canopy removal, and/or the species involved. In the case of black spruce (*Picea mariana*), response to release was positively correlated with height for trees smaller than 2 m, but negatively correlated for the taller trees (Lussier *et al.* 1992). However, even when the response of the taller advance regeneration is slower, it can add significantly to the yield of second growth stands (Pothier *et al.* 1995, Riopel 1999).

In this study, a similar trend was found for all three of the species analysed (Douglas-fir, lodgepole pine, and interior spruce) for small tree height growth (Figure 1 to 3): five-year height growth increased with an increase of tree total height, up to a point, after which it decreased. The correlation coefficient between total height and the five-year height growth was negative

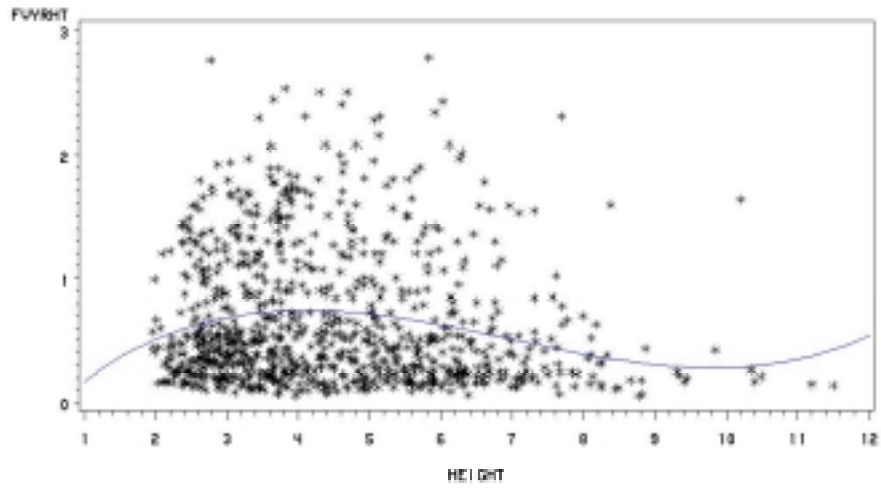


Figure 1. Height growth vs. total height for Douglas-fir.

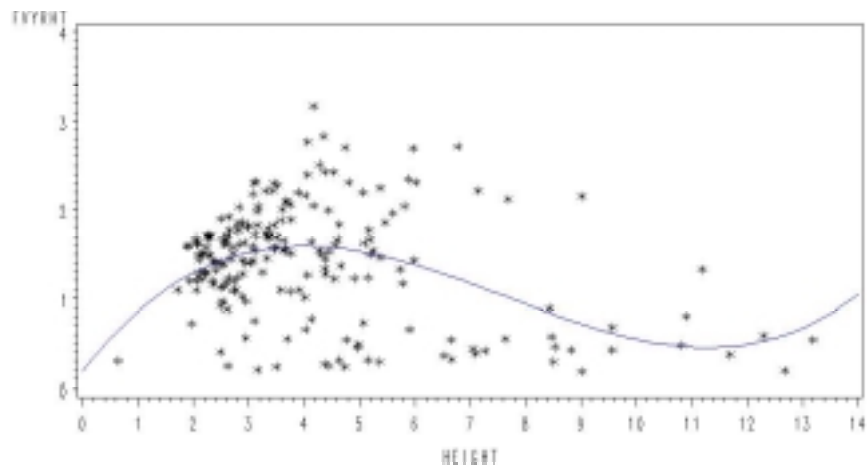


Figure 2. Height growth vs. total height for lodgepole pine.

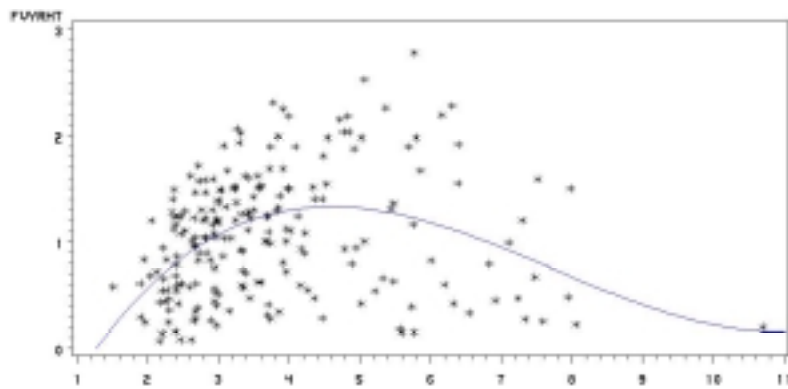


Figure 3. Height growth vs. total height for spruce.

and significant for Douglas-fir and lodgepole pine ($\alpha=0.05$) and positive and non-significant ($\alpha=0.05$) for interior spruce. The trend for Douglas-fir and lodgepole pine can be explained by the fact that many of the taller trees sampled were located in dense plots and were actually relatively old trees with a slow rate of growth. Spruce is the most shade tolerant of the species considered and the least affected one by the density of the stand.

3.3.1.2 Ecological variables

The only ecological variable identified for each plot was the BEC site series. This is a qualitative variable. However, to determine the BEC site series, the percentage cover of shrubs and the percent cover of herbs (collectively, understory vegetation) had to be determined. The percent covers of shrubs and herbs were used as independent variables for predicting small tree height growth.

The relationship of the percent cover of herbs and the percent cover of shrubs with small tree height growth is illustrated in Figures 4 to 9. For Douglas-fir and lodgepole pine, no apparent trend is visible. This fact was confirmed by the correlation coefficients, which were non-significant ($\alpha = 0.05$). For spruce, a significant negative correlation ($\alpha = 0.05$) was found between the percent cover of both herbs and shrubs and the five-year height growth. Although not significant, the correlation coefficients between percentage cover for herbs and shrubs and five-year height growth of lodgepole pine were negative as well. The only positive correlation was found between the five-year height growth of Douglas-fir and the percent cover of the shrub layer. This circumstantial correlation was found only on open, dryer sites with sparse vegetation with few small trees, where the competition with the understory was apparently not very intense.

3.3.1.3 Topographic Variables

Although topographic variables were implicitly involved in determining the BEC subzones and site series, they were also used, after transformation, as independent variables to predict small tree height growth. Topographical variables were a component in the original small tree height growth model in Prognosis. The interaction between slope and aspect was thought to be especially important for modelling height growth (Stage 1976).

- 1) Aspect: measured in degrees with a compass to the nearest degree. Sine (+) and cosine (-) of the aspect were highly correlated with the five year height growth for all tree species analyzed.
- 2) Slope: measured in percent with a Suunto clinometer to the nearest percent. Surprisingly, slope was positively correlated only with Douglas-fir five-year height growth (Figure 10). The only explanation for this result is that as slope increases, the density of the stand decreases (the correlation between the slope and the number of trees per hectare, for instance, was found to be negative and significant ($\alpha = 0.05$)).

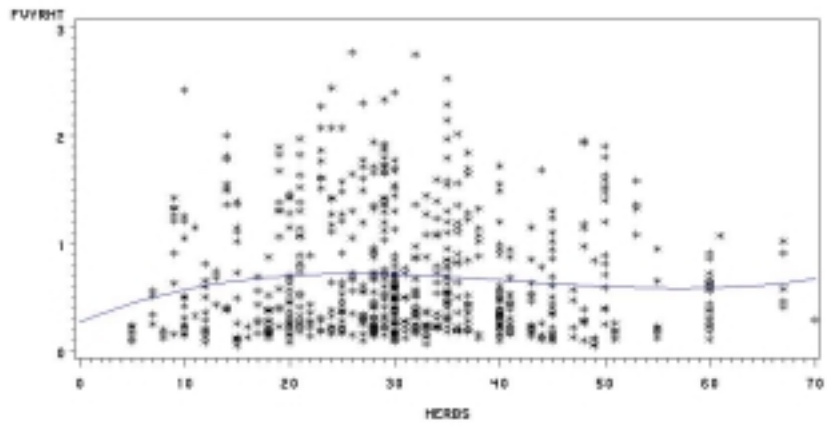


Figure 4. Five-year height growth vs. percent cover of herbs for Douglas-fir

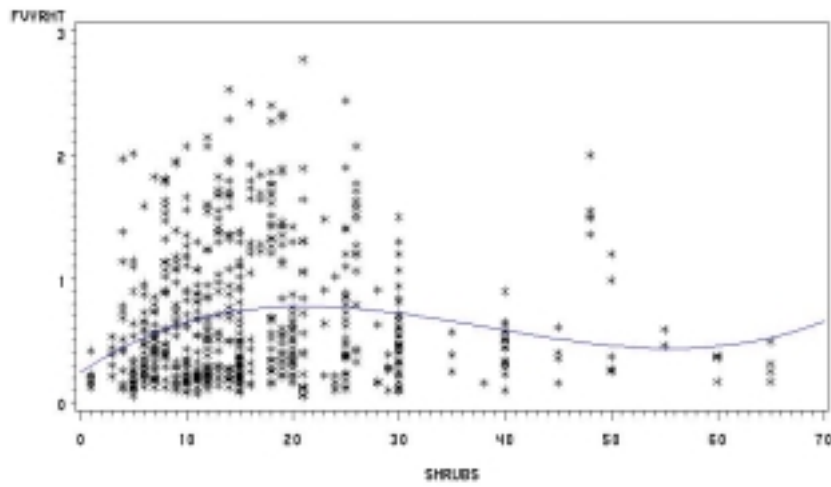


Figure 5. Five-year height growth vs. percent shrub cover for Douglas-fir.

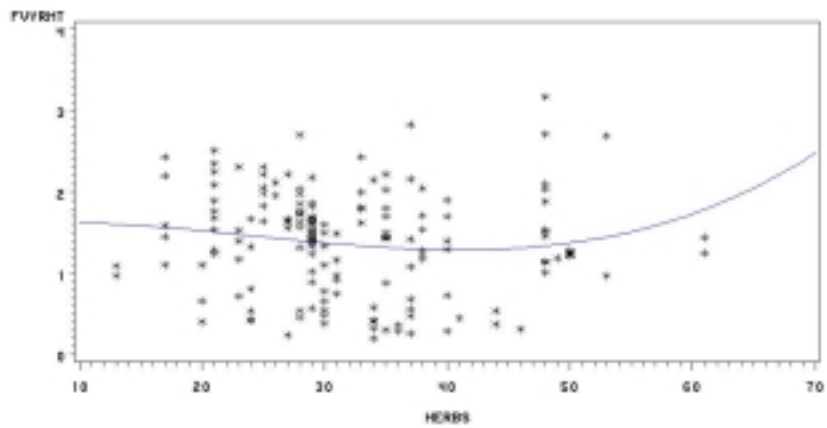


Figure 6. Five-year height growth vs. percent cover of herbs for lodgepole pine.

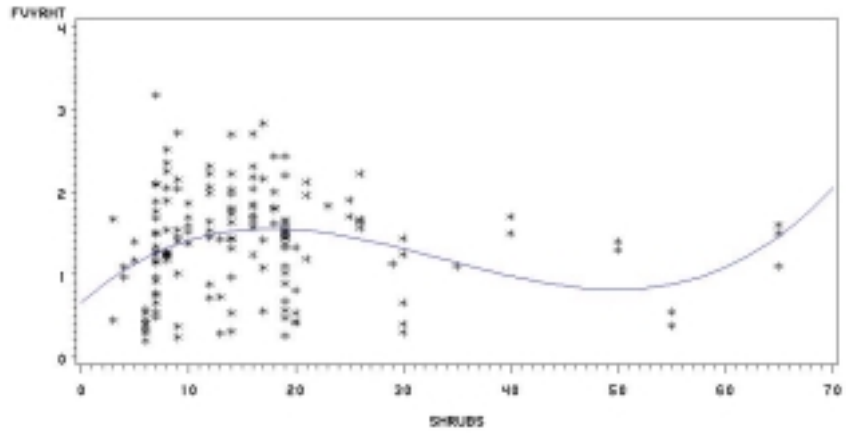


Figure 7. Five-year height growth vs. percent shrub cover for lodgepole pine.

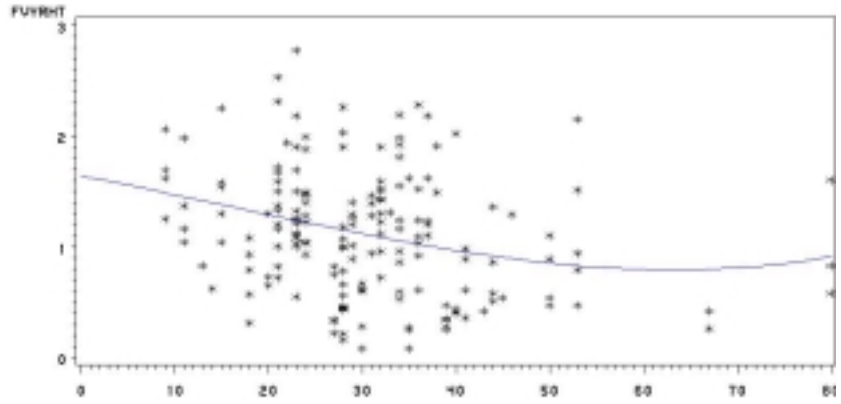


Figure 8. Five-year height growth vs. percent herb cover for spruce.

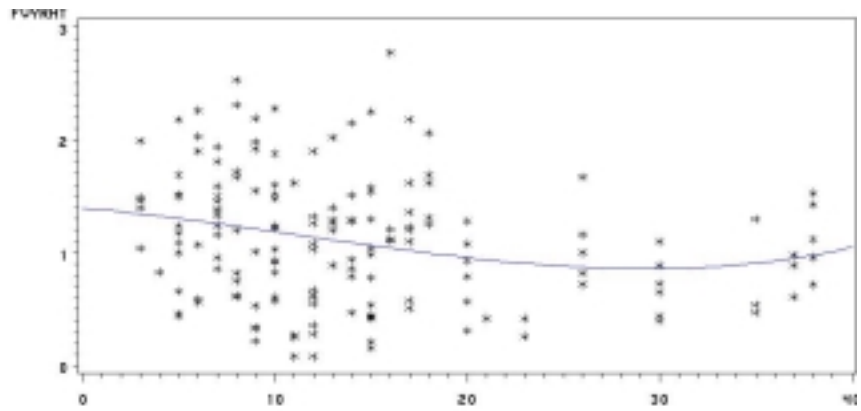


Figure 9. Five-year height growth vs. percent shrub cover for spruce.

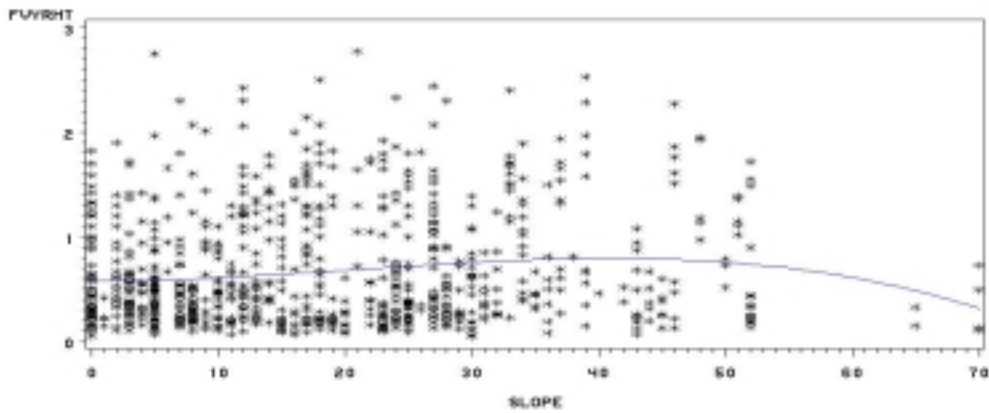


Figure 10. Five-year height growth vs. slope for Douglas-fir

3) Elevation: recorded in m. This was not a component in the original Prognosis small tree height growth model, but was used as an independent variable in this analysis. The correlation between five-year height growth and elevation was negative and non-significant ($\alpha = 0.05$) for all three species. The trend for all species was initially an increase in five-year height growth with elevation followed by a decrease in height growth (Figures 11 to 13).

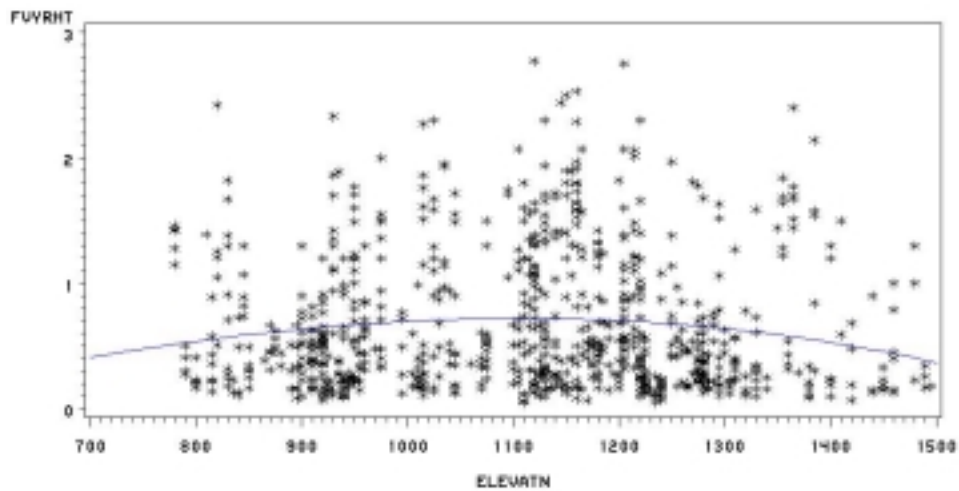


Figure 11. Five-year height growth vs, elevation for Douglas-fir

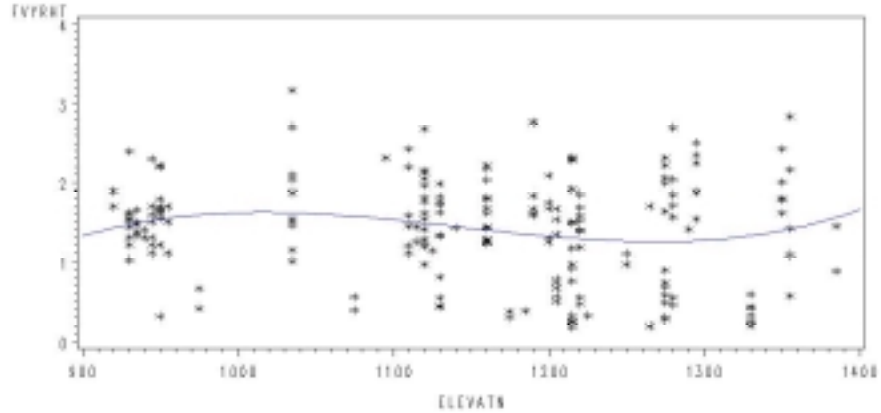


Figure 12. Five-year height growth vs. elevation for lodgepole pine.

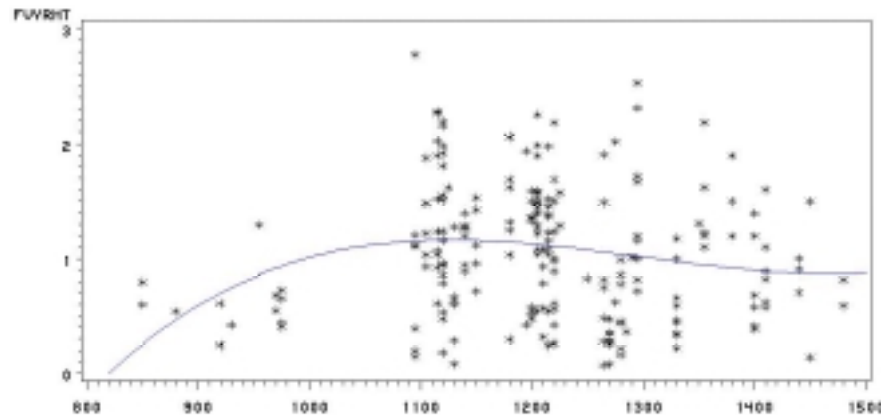


Figure 13. Five-year height growth vs. elevation for spruce

3.3.1.4 Years since disturbance

Some studies have shown that height growth does not respond immediately to release and in some cases it can be reduced to levels below those observed before release (e.g., Nikinmaa 1993, Williams 1996). Part of this delayed response could be attributed to the fact that height growth is often predetermined in the previous growing season (Aussenac 1977); however, this would not be sufficient to explain growth reduction or delays exceeding one year found in many studies. Height growth response can also be immediate, especially for the smaller trees and regeneration (Seidel 1989). Messier *et al.* (1999) suggested that the light requirements of seedlings increase with size. Thus, shorter trees might be less stressed at a given level of light than taller ones, and so could adjust to the altered growing environment more readily. Shade tolerant species may also adjust more readily than less tolerant seedlings of the same size.

For all the species considered in this study, correlation analysis revealed a significant positive correlation between five-year height growth and the time since last disturbance (Figures 14 to 16). The trends shown by the various species were similar, although the effect of release was immediate for spruce and lodgepole pine and delayed about four or five years for Douglas-fir.

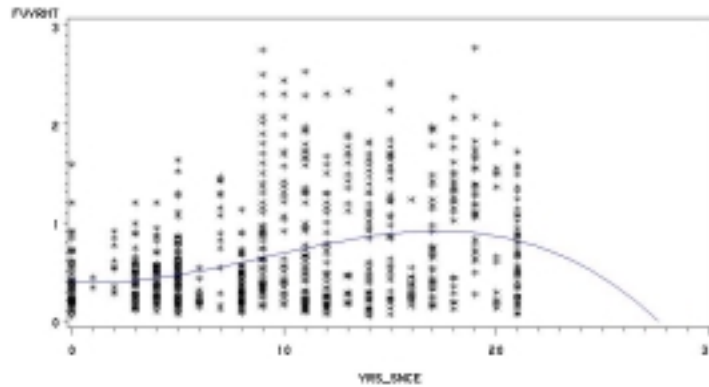


Figure 14. Five-year height growth vs. years since disturbance for Douglas-fir

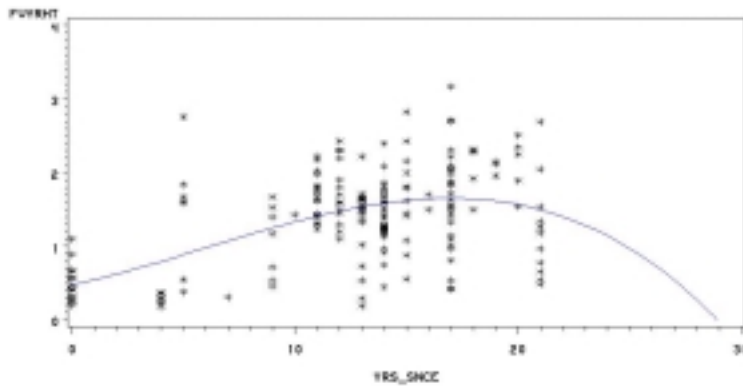


Figure 15. Five-year height growth vs. years since disturbance for lodgepole pine.

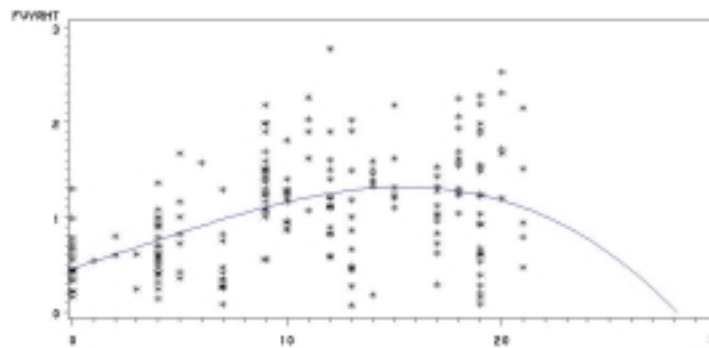


Figure 16. Five-year height growth vs. years since disturbance for spruce

3.3.2 Derived Attributes

The derived attributes obtained and used in this report can be grouped as follows: individual tree attributes, stand density/competition attributes, stand structure attributes, and site index.

3.3.2.1 Individual Tree Attributes

- 1) Shape was determined as the height/diameter ratio. Some conifer species have been found to change their height/diameter ratio in response to changes in the understory environment (Lieffers and Stadt 1994). Gavrikov and Sekretenko (1996) found Scots pine's (*Pinus sylvestris*) diameter growth to be much more sensitive to environmental change than height growth. Height growth of true firs (*Abies* spp.) was found to be much more sensitive to overstory canopy shade than diameter growth (Duchesneau *et al.* 2000). For a certain height, the height/diameter ratio is higher for shade-intolerant than tolerant species and for deciduous compared to coniferous saplings (Hara *et al.* 1991). Hara *et al.* (1991) suggested that shade-tolerant species maintain their diameter growth in shade because they tend to maintain a much larger foliage biomass than shade-intolerant species. Consequently, one should expect intolerant and mid-tolerant species like pines (*Pinus* spp.) to show stronger height/diameter ratio responses than tolerant species such as true firs (Duchesneau *et al.* 2000, Williams *et al.* 1999).

The correlation between height growth and height/diameter ratio was negative for all the tree species examined, but very strongly correlated only for lodgepole pine (Figures 17 to 19).

3.3.2.2 Stand Density Attributes

- 1) Trees per hectare (TPH). This is the mean density for the stand (plot). In plant and animal ecology, density is commonly defined as number of individuals per unit area. In forest stands, definition of density as the number of individuals per unit area is of limited usefulness because trees increase in size more or less indefinitely and change in dimensions and ability to utilise site resources in response to the influence of adjacent trees (Curtis 1970). Therefore, other measures of density or competition are more readily used in describing or deriving characteristics of a forest stand.

The correlation between TPH and five-year height growth was negative for the three species analysed; however, the correlation was significant ($\alpha=0.05$) only for Douglas-fir (Figures 20 to 22). It can be seen that the five-year height growth of lodgepole pine starts to decline only at high levels of crowding. This is a known characteristic of this species (BCMoF 1995). Spruce is more shade tolerant and therefore less affected than Douglas-fir by the density of the stand.

- 2) Basal area (BA). Although Curtis (1970) argues that a more meaningful measure of density would be the relative basal area, basal area has been widely used as an indicator of density. Basal area was considered by Vanclay (1994) as an indicator of a 'two-sided' competition, competition for resources other than light, including moisture and nutrients.

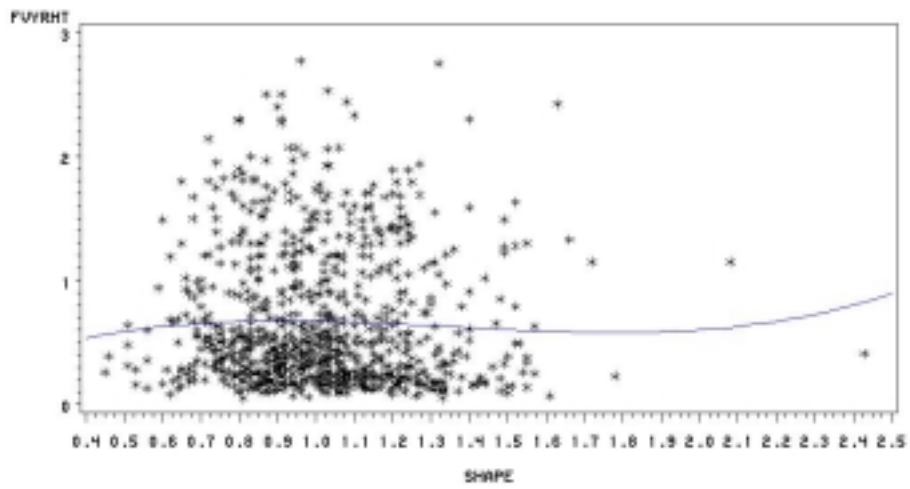


Figure 17. Five-year height growth vs. height/diameter ratio for Douglas-fir.

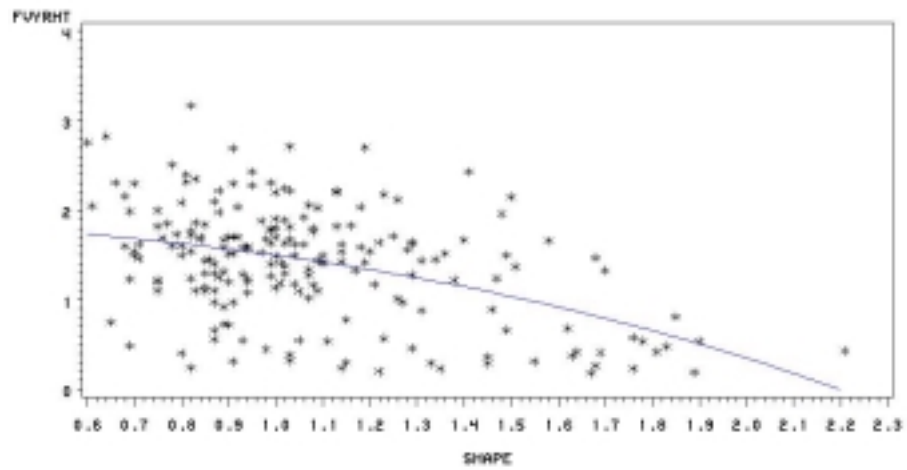


Figure 18. Five-year height growth vs. height/diameter ratio for lodgepole pine.

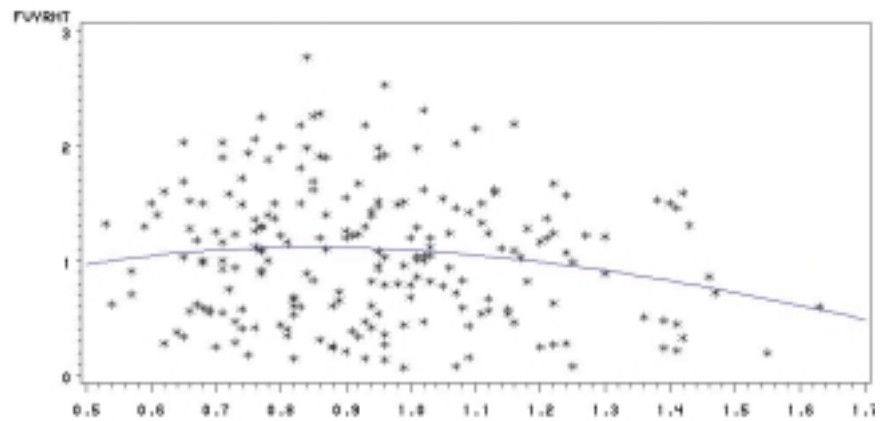


Figure 19. Five-year height growth vs. height/diameter ratio for spruce

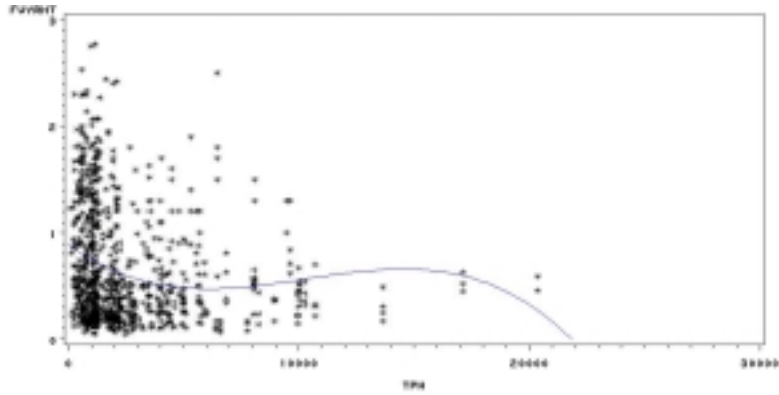


Figure 20. Five-year height growth vs. TPH for Douglas-fir

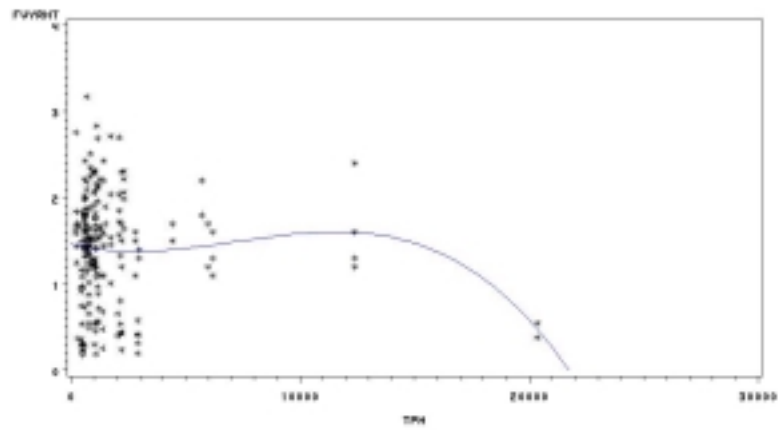


Figure 21. Five-year height growth vs. TPH for lodgepole pine.

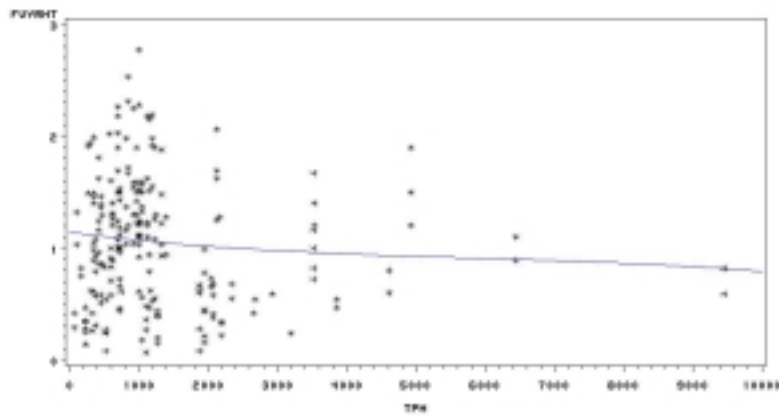


Figure 22. Five-year height growth vs. TPH for spruce

For the three species examined, a strong negative correlation was found between the basal area of the stand and the five-year height growth of the small trees (Figures 23 to 25).

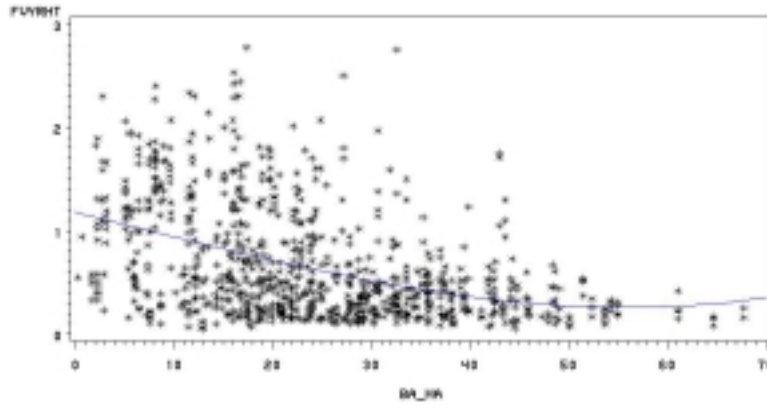


Figure 23. Five-year height growth vs. BA/HA for Douglas-fir.

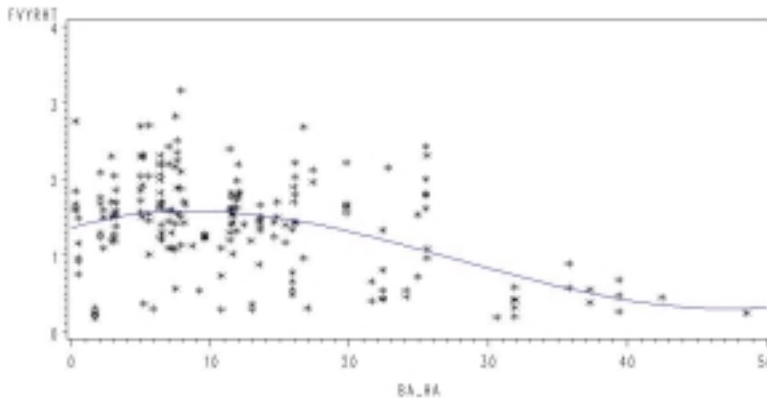


Figure 24. Five-year height growth vs. BA/HA for lodgepole pine.

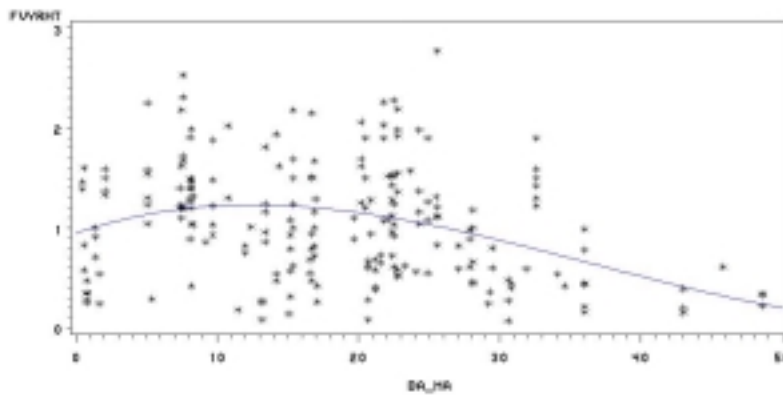


Figure 25. Five-year height growth vs. BA/HA for spruce

3) Basal Area in Larger Trees (BAL). BAL has been found to be a useful predictor of diameter growth (Wykoff 1990) and considered to be analogous to available light. Several researchers (e.g. Hara 1986) have suggested that competition among plants in a monoculture is mainly for light, rather than for other environmental resources. This may imply that a component of competition is “one-sided”; bigger trees shade smaller ones and not vice-versa. This can make BAL a useful predictor and complementary to basal area, which can represent “two-sided” competition.

For the three species examined in this study, the correlation between small tree five-year height growth and BAL was negative and significant (figures 26 to 28).

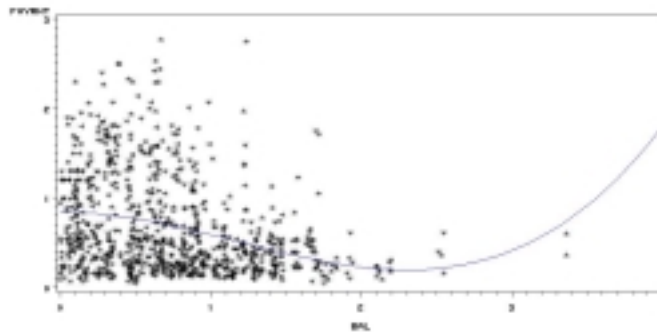


Figure 26. Five-year height growth vs. BAL for Douglas-fir.

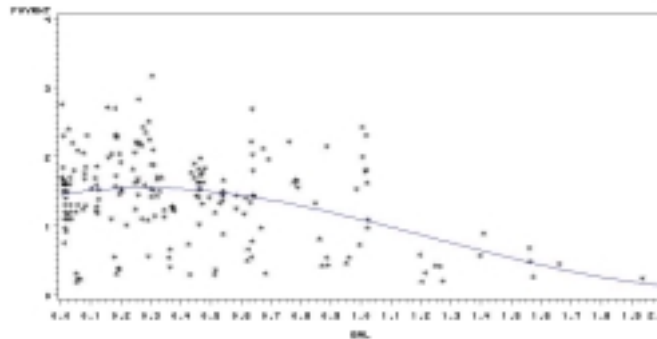


Figure 27. Five-year height growth vs. BAL for lodgepole pine.

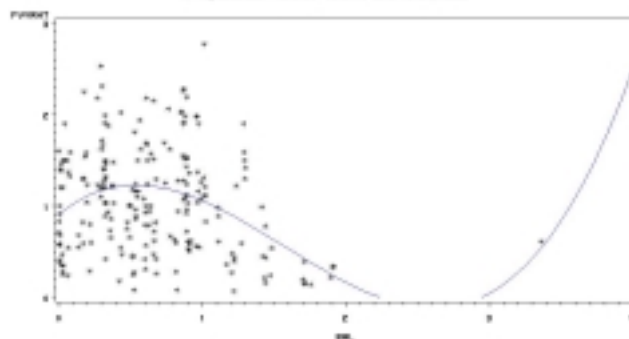


Figure 28. Five-year height growth vs. BAL for spruce

4) Crown Competition Factor (CCF). This quantity was calculated based on the original Prognosis code for CCF, which more or less follow the idea developed by Krajicek *et al.* (1961). In Prognosis, the coefficients for calculating CCF are species specific.

For all species in this study a strong negative correlation was found between small tree height growth and CCF (Figures 29 to 31).

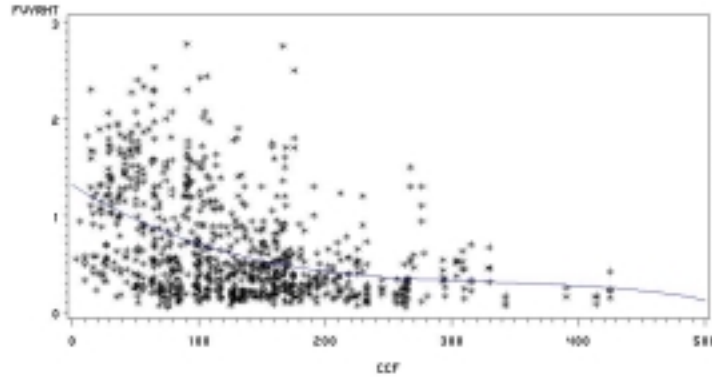


Figure 29. Five-year height growth vs. CCF for Douglas-fir.

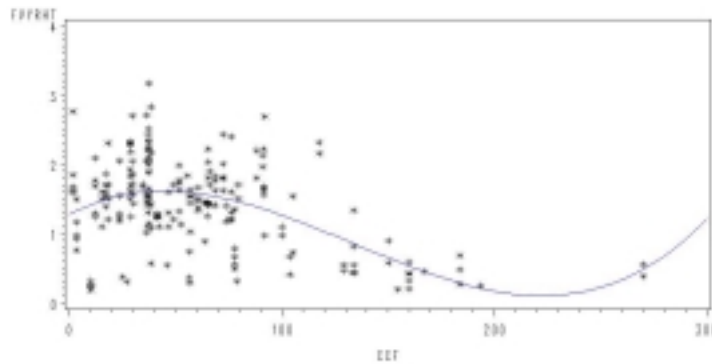


Figure 30. Five-year height growth vs. CCF for lodgepole pine.

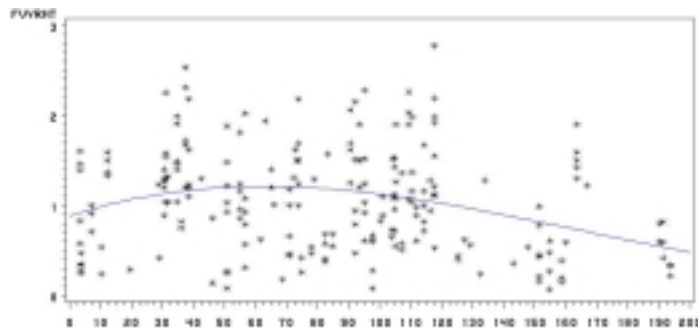


Figure 31. Five-year height growth vs. CCF for spruce.

5) Quadratic Mean Diameter (QMD). This is the dbh of the tree of average basal area. The quadratic mean diameter is a widely used descriptor of average tree size and is used as a basis for determining stand density in stocking guides such as those developed by Gingrich (1976). Weatherhead *et al.* (1985) found that QMD is independent of density for any balanced diameter distribution, with a specified maximum tree size, class width and quotient q . It was found also that QMD becomes relatively insensitive to increasing of maximum tree size as the quotient increases.

QMD had a strong negative correlation with TPH for all species analyzed. For small tree five-year height growth, QMD had a strong negative correlation for Douglas-fir and lodgepole pine, but not for spruce. Spruce, being more shade tolerant than the other two species, can better stand competition exerted by larger trees from above. The trends between five-year height growth and QMD in Figures 32 to 34 appear to be the opposite of this: the five-year height growth of spruce decreases with an increase in QMD while that of Douglas-fir and lodgepole pine is relatively unaffected. This trend is likely caused by a confounding of other factors.

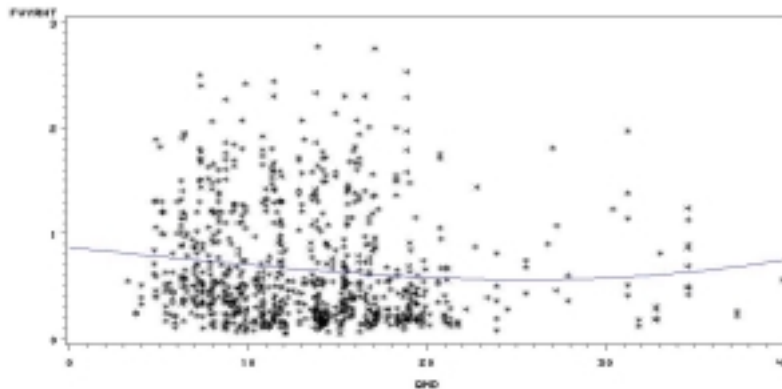


Figure 32. Five-year height growth vs. QMD for Douglas-fir.

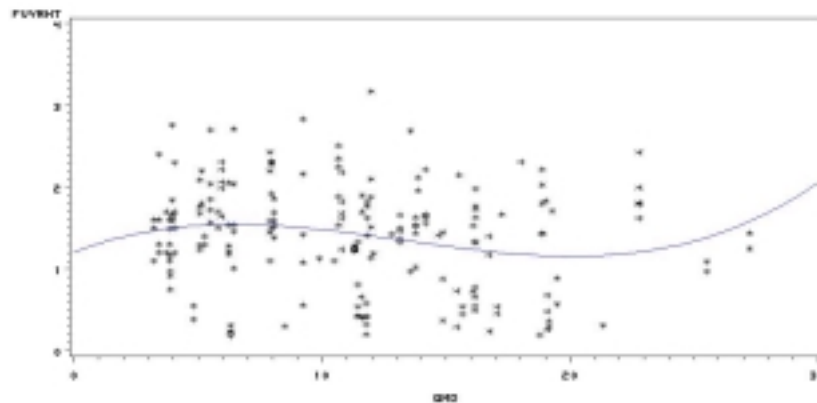


Figure 33. Five-year height growth vs. QMD for lodgepole pine.

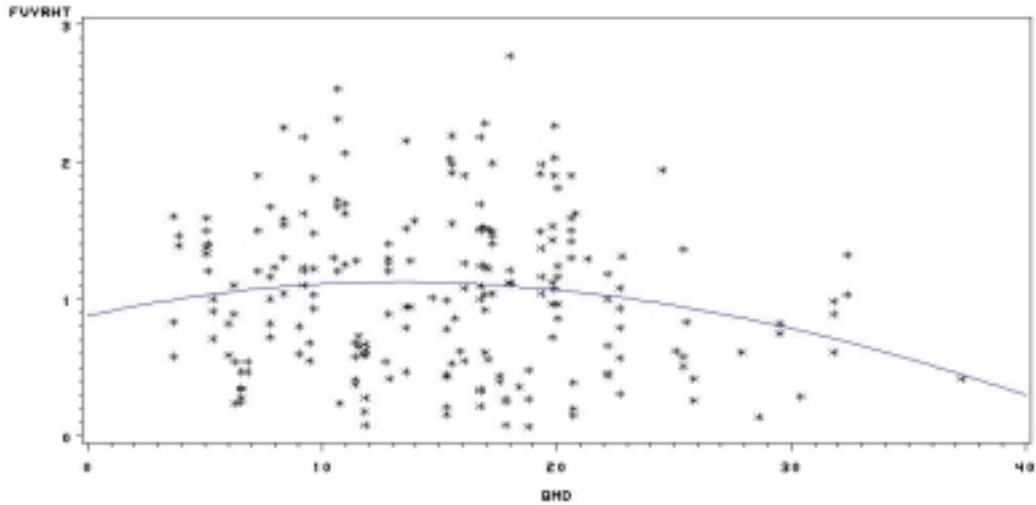


Figure 34. Five-year height growth vs. QMD for spruce.

6. *Curtis' (1982) Relative Density Index (RD)*. This index, a variation of Reineke's (1933) stand density index (SDI), was determined for each plot. The higher the value of RD, the greater the density of the stand.

The correlation between RD and the five-year height growth of the three species was found to be strongly negative correlated, as expected (Figures 35 to 37).

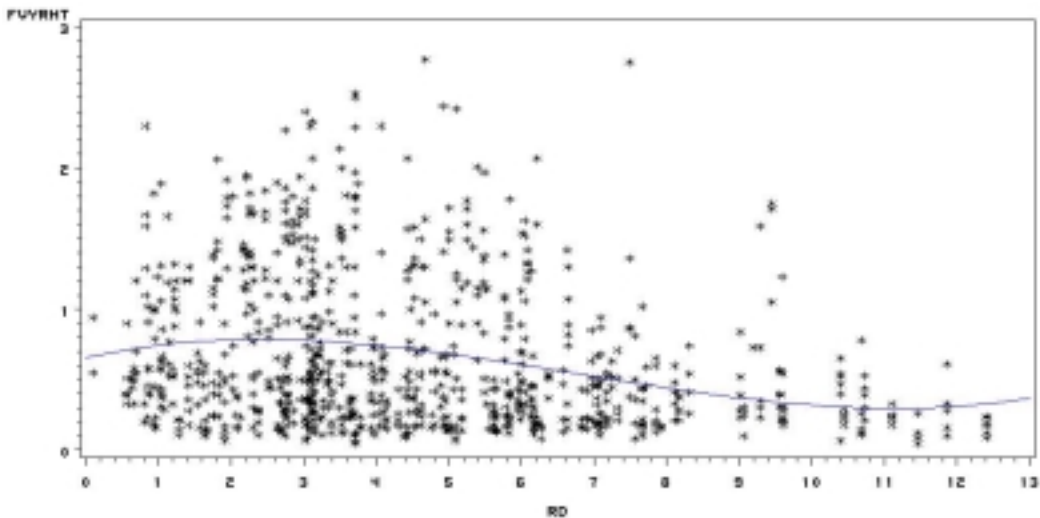


Figure 35. Five-year height growth vs. RD for Douglas-fir.

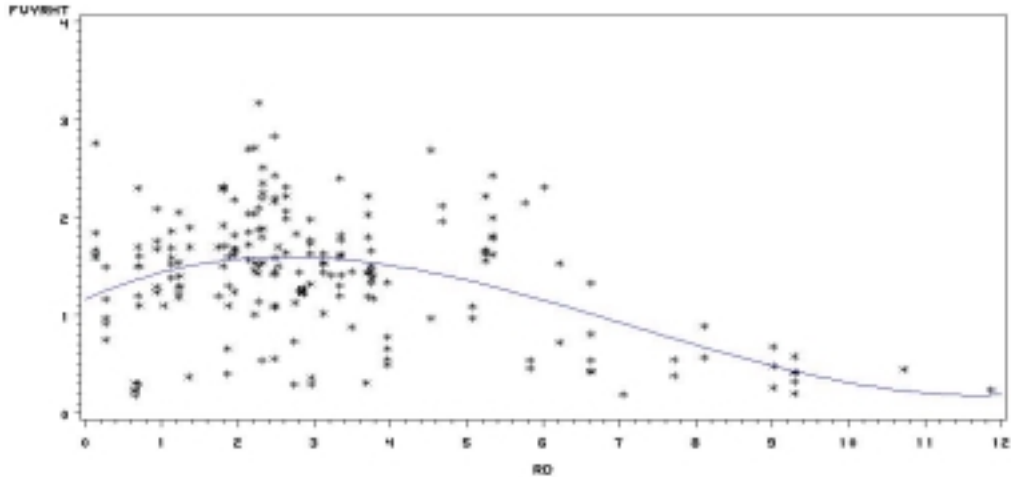


Figure 36. Five-year height growth vs. RD for lodgepole pine.

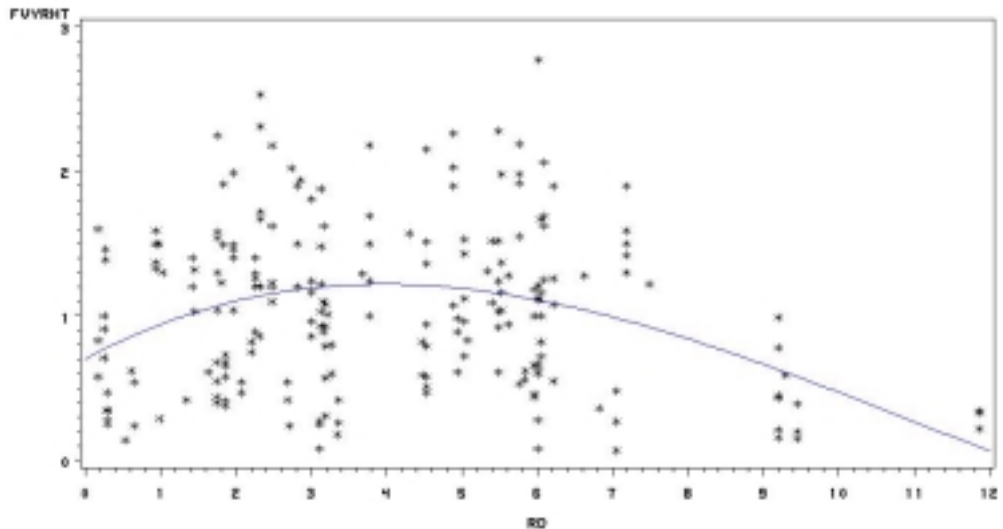


Figure 37. Five-year height growth vs. RD for spruce.

7) Stand Density Index (SDI). SDI was calculated using the formula provided by Long (1985): $SDI = (TPH) \times (QMD/25)^{1.6}$. The higher the value of SDI, the denser the stand.

A strong negative correlation was found for three species between five-year small tree height growth and SDI, as expected (Figures 38 to 40).

3.3.2.3 Stand Structure Attributes

1) De Liocourt's quotient (q). This is a widely implemented measure of stand structure in uneven-aged stands. q was calculated for each treatment using the least-squares method described by Leak (1963). The number of trees per ha were listed by 5 cm dbh classes for each stand and q was computed using all trees with dbh's greater than or equal to 2.5 cm.

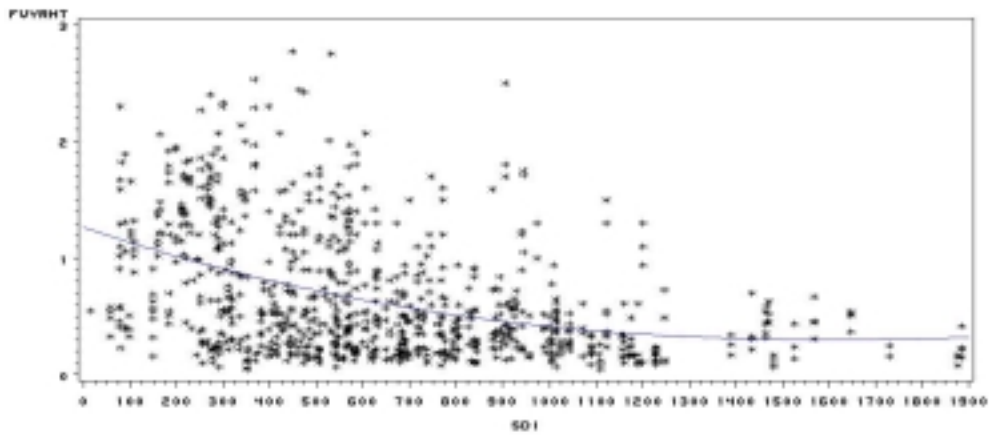


Figure 38. Five-year height growth vs. SDI for Douglas-fir.

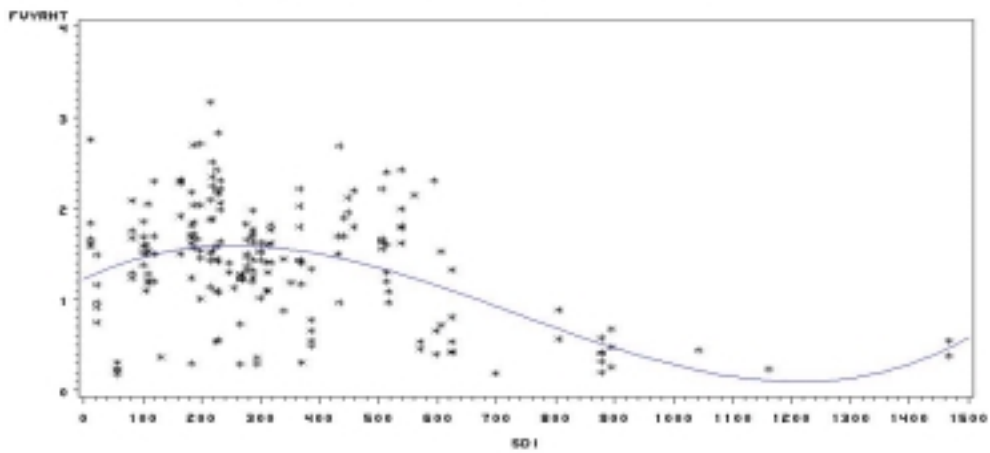


Figure 39. Five-year height growth vs. SDI for lodgepole pine.

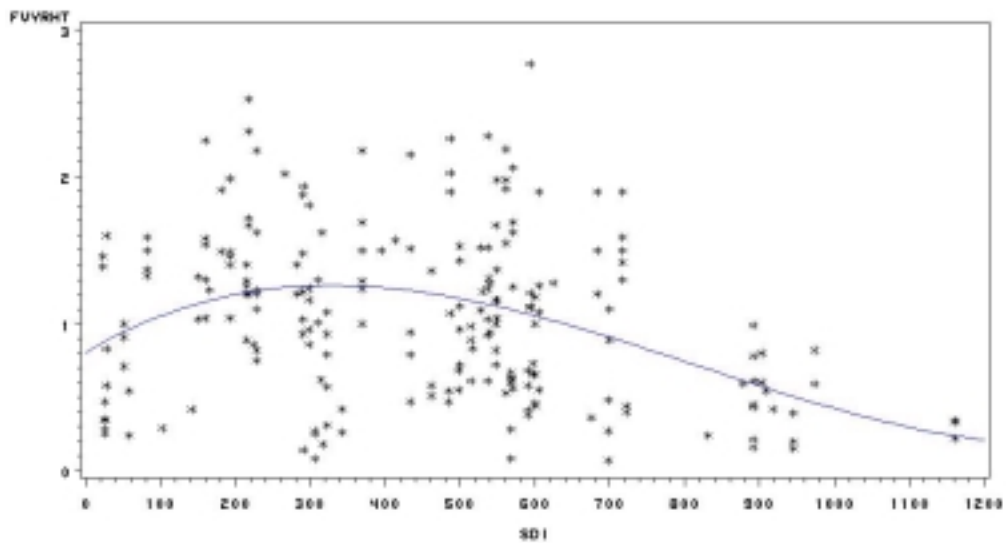


Figure 40. Five-year height growth vs. SDI for spruce.

As expected, the correlation between q and almost all density indices for all species was negative and significant. The correlation between the quotient and five-year small tree height growth for Douglas-fir was not significant (Figure 41). This fact is in agreement with the wide range of stand structures in which small Douglas-fir were found. A significant positive correlation was found between q and five-year small tree height growth for lodgepole pine and spruce, which indicates that these species tend to grow better in stands where smaller diameter classes are better represented (Figure 42 and 43).

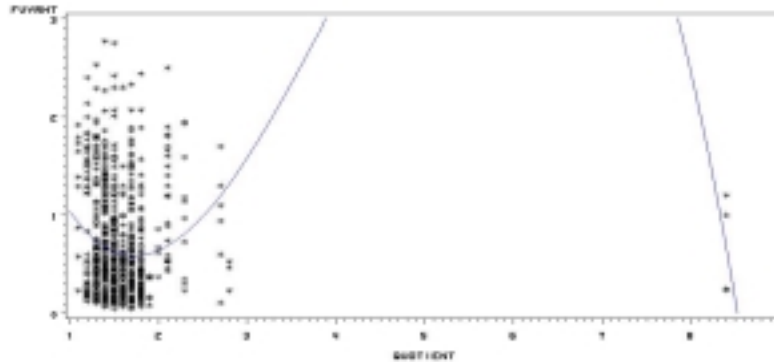


Figure 41. Five-year height growth versus q for Douglas-fir.

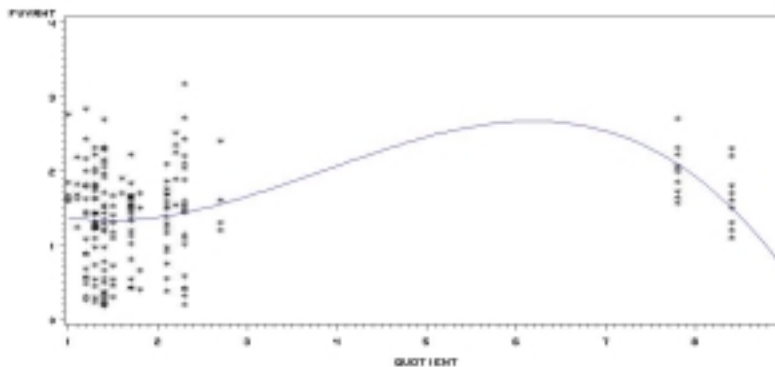


Figure 42. Five-year height growth vs. q for lodgepole pine.

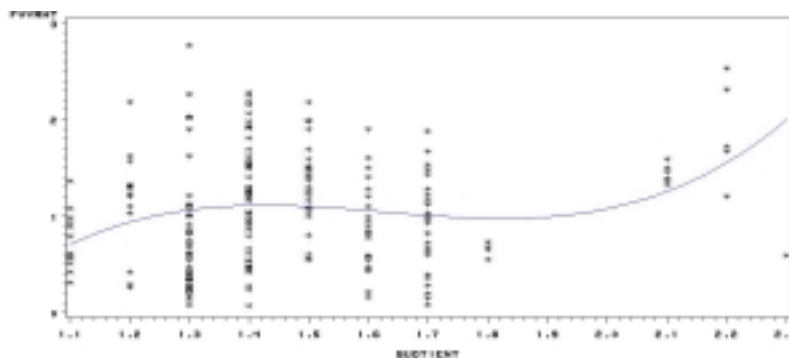


Figure 43. Five-year height growth vs. q for spruce

2) Shannon's Index (H'). This index was based on basal area by diameter classes and was calculated as follows:

$$H' = - \sum_{i=1}^S p_i \ln p_i,$$

where p_i is the proportion of basal area per ha by 5 cm dbh classes in the i^{th} diameter class, \ln is the natural logarithm, and S is the number of diameter classes. The index describes the horizontal diversity within the stand. The index is not sensitive to tree size or number, as indices are weighted only on the proportion of basal area occurring in a particular class. The maximum value for Shannon's index occurs when the proportions are equal over all classes, resulting in a value equal to the natural logarithm of S . The correlation between q and Shannon's index is negative and significant. Generally, large values of q imply that a large proportion of the trees are grouped in the first one or two diameter classes. If there are only small trees present, q probably would be high and H' would be low. The reverse argument holds if there are several dbh classes present.

The correlation between five-year small tree height growth and H' was negative and significant for all species (Figures 44 to 46).

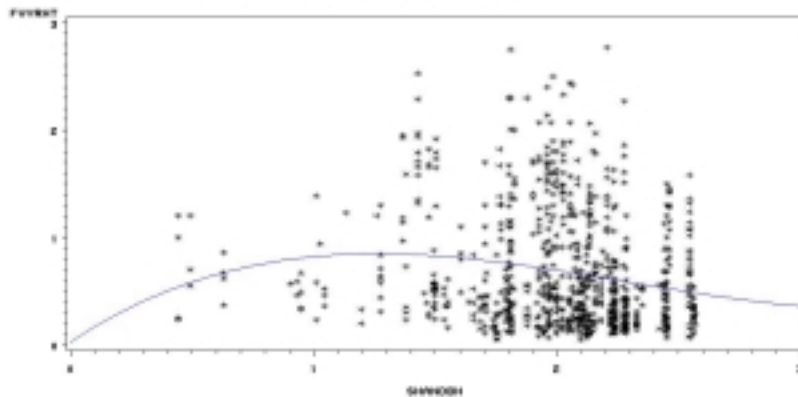


Figure 44. Five-year height growth vs. Shannon's index for Douglas-fir.

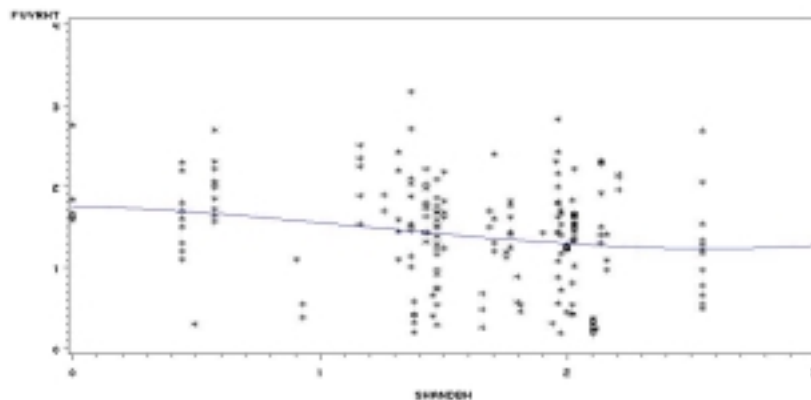


Figure 45. Five-year height growth vs. Shannon's Index for lodgepole pine.

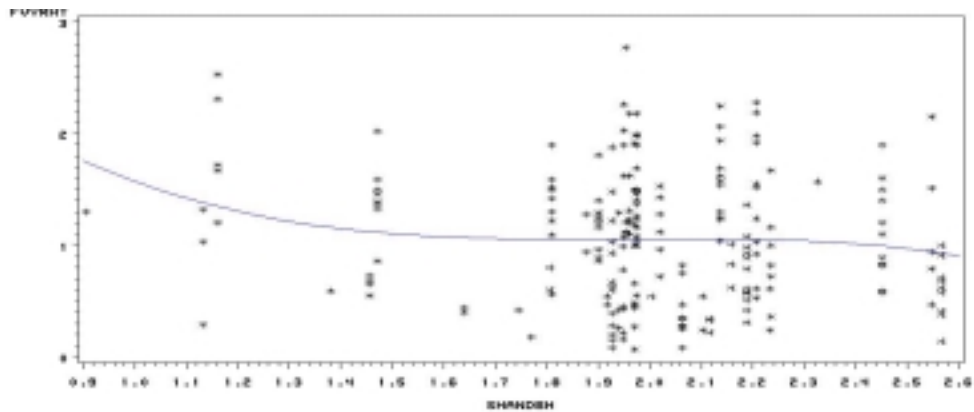


Figure 46. Five-year height growth vs. Shannon's Index for spruce.

3) Structural Index Based on Variance (STVI). This index is based on a comparison of the variance of the basal area distribution of a stand to the variance of a uniform distribution of basal area, which represents maximum structural diversity (Staudhammer and LeMay 2000). The index was calculated using 5 cm dbh classes, on a stand basis, for dbh's between 0 and 150 cm using the formulas provided by LeMay and Staudhammer (2000a).

The correlation between STVI and Shannon's Index was positive and quite strong. Surprisingly, a nonsignificant negative correlation was found between five-year small tree height growth for the three species and STVIDBH (Figures 47 to 49).

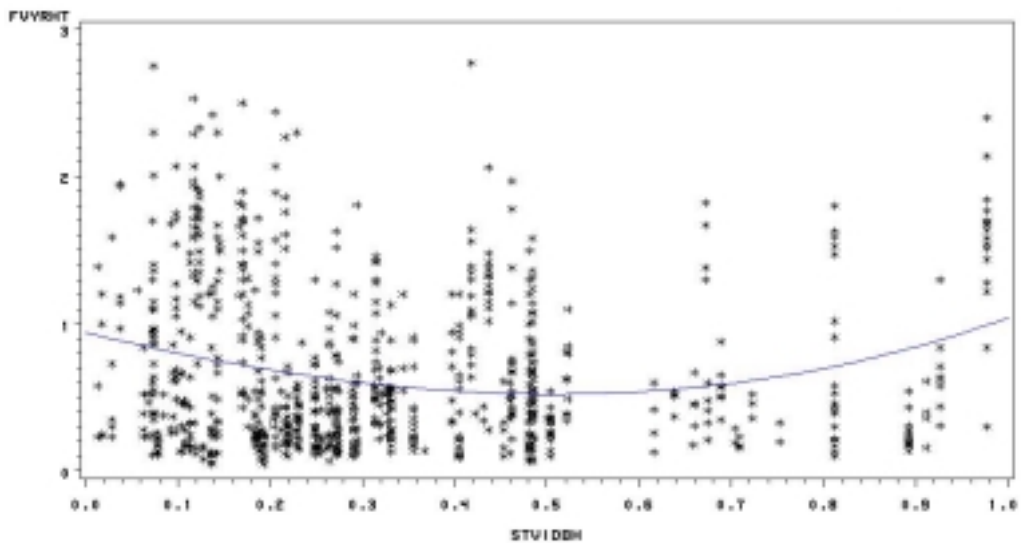


Figure 47. Five-year height growth vs. STVI for Douglas-fir.

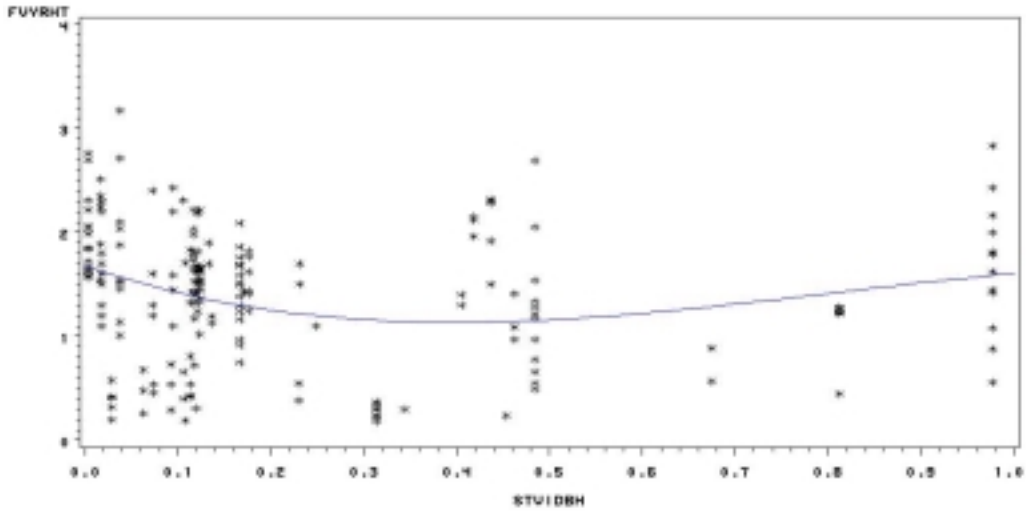


Figure 48. Five-year height growth vs. STVI for lodgepole pine.

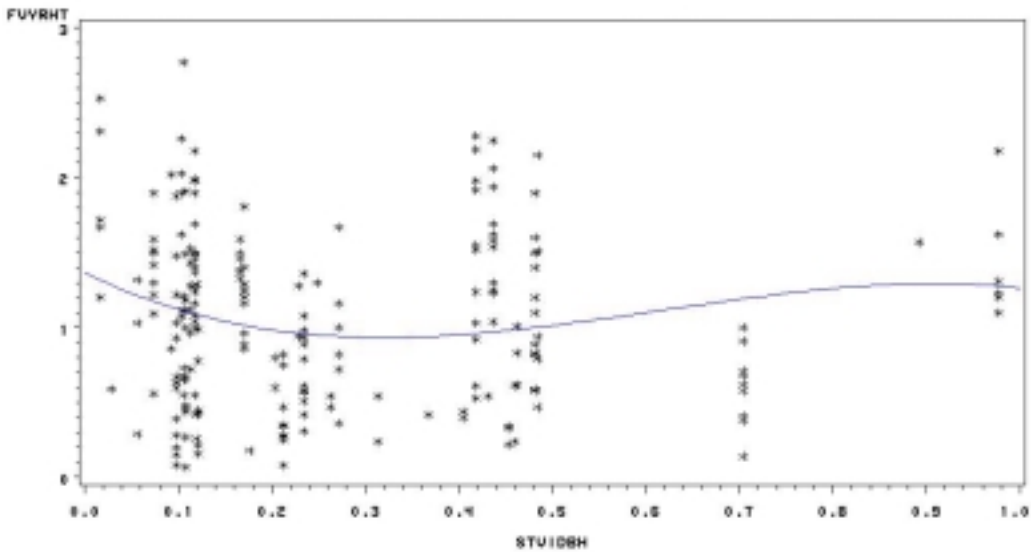


Figure 49. Five-year height growth vs. STVI for spruce.

3.3.2.4 Site Index

The only descriptor for site growth potential used in this report is site index (SI). SI is an indicator of the potential height growth on a site for a given tree species over a fixed time period. It is defined as the average height of top height trees of a certain species at 50 years breast height age (bha).

For this project SI was not determined on site because sampling was done mostly in uneven-aged stand, unsuited for determining and using site index using direct measurement of height and bha. Rather, SI was derived using equations that relate the BEC site series to site index (FRBC and

BCMoF 1997). This method was considered suitable for the purpose of the present project because the accuracy required is moderate and correct site identification of each plot was available.

The correlation between site index and five-year height growth was found to be significant and positive for Douglas-fir and lodgepole pine and significant and negative for spruce (Figures 50 to 52). A possible explanation for the relationship with five-year height growth for spruce was that spruce on better sites could be found in denser stands which would decrease their growth. However, was not tested in a covariance analysis.

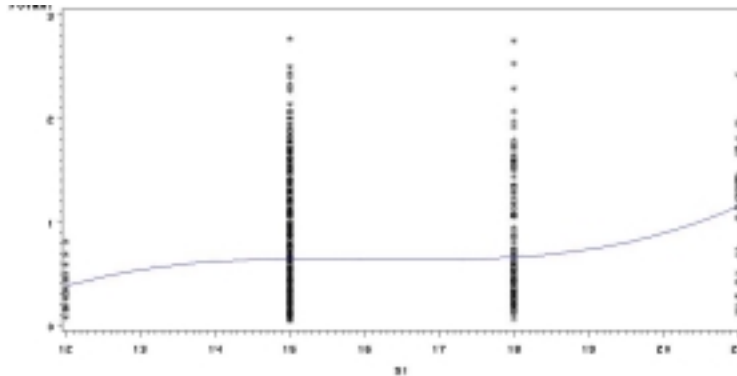


Figure 50. Five-year height growth vs. SI for Douglas-fir.

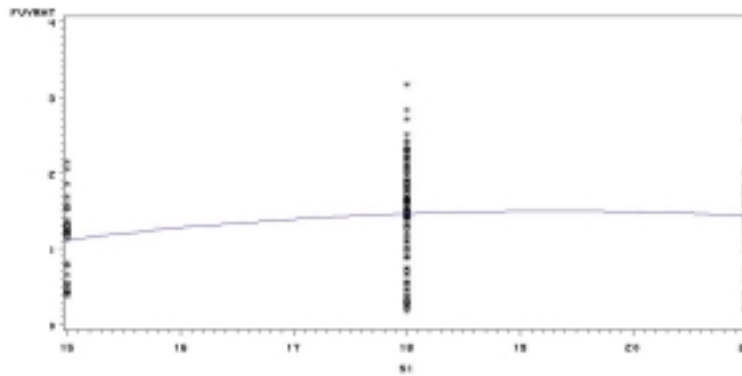


Figure 51. Five-year height growth vs. SI for lodgepole pine.

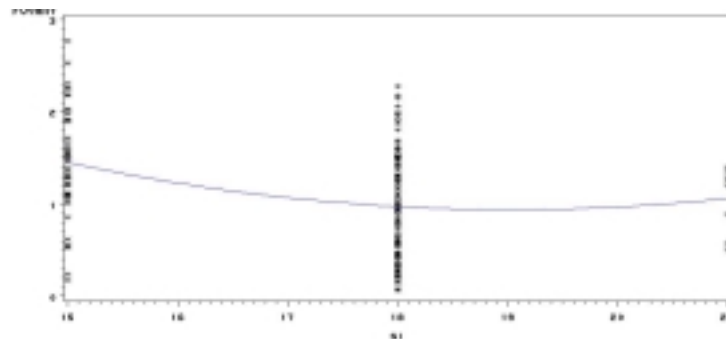


Figure 52. Five-year height growth vs. SI for spruce.

3.4 Models for Predicting Five-Year Small Tree Height Growth

Preliminary work was presented in Lencar and Marshall (2000). These results showed that the Prognosis NI model behaved inconsistently for different the various BEC subzones/variants and species. For Douglas-fir, the model overestimated height growth, but no general trend was noticed since the residuals were distributed uniformly across the entire range of predicted values. For spruce and lodgepole pine, predictions were less consistent. This could be due to the fact that far less observations exist for the later two species than for Douglas-fir.

It was assumed that the refitting the Prognosis model for the actual data would improve the behaviour of the equations. Other variables and model forms were also explored in order to see whether better predictions could be obtained.

Pooling the data from IDFdk1, IDFdk2 and IDFdk3 was a necessary step in developing a better model. The Prognosis small tree height growth model was re-fit using OLS for all the pooled data for the Prognosis NI original variables plus QMD and RD (M-1). The best subset of these variables was used non-linear model (M-2). A third model form explored the use of the square root of five-year height growth as the dependant variable (M-3). A model that used five-year height growth as a dependant variable and height and height squared as independent variables was discarded from the beginning because of the poor results. Additionally, several other variables were added to the M-1 set in an attempt to improve the estimates (M-1.1, M-1.2).

The linear, linearized and non-linear models used for predicting small tree height growth were evaluated by comparing residuals, R^2 values, F^2 values ($1 - (SS_{res}/SS_{tot})$), the standard error of the estimate ($SEE = \sqrt{SS_{res}/df}$) and bias ($Bias = (\sum (y_i - \hat{y}_i))/n$). In all analyses, results were evaluated at the 0.05 significance level. Linear or linearized models were selected based on the best adjusted R^2 ($AdjR^2 = [(n - i)(1 - R^2)] / (n - p)$).

All statistical analyses were performed with SAS (Version 6.12), while spreadsheet manipulations were performed with Excel (Microsoft 1997).

4.0 Results

Fit statistics, scatterplots of residuals and normality tests for all the models were used to make comparisons among models and species. Residual plots and normality tests suggested no remaining nonlinearly or bias for any of the final five-year height growth models for the three species (Table 2). Fit statistics are given in Table 3.

Table 2. Summary of the final five-year height growth equations.

Species	n	Model	Equation Form
Fd	882	M-1	LN(HTG)=F(dss, ln_ht, height, sl_ratio, sin_slpe, cos_slpe, CCF, BAL, QMD, elevation)
	882	M-1.1	LN(HTG)=F(dss, ln_ht, height, sl_ratio, sin_slpe, cos_slpe, CCF, BAL, QMD, elevation, Shape, time)
	675	M-1.2	LN(HTG)=F(dss, ln_ht, height, sl_ratio, sin_slpe, cos_slpe, CCF, BA_HA, BAL, QMD, RD, time, herbs, shrubs)
	882	M-2	HTG=EXP(dss, ln_ht, height, sl_ratio, CCF, BAL)
	882	M-3	SQRT(HTG)=F(dss, ln_ht, height, sin_slpe, cos_slpe, CCF, BAL, QMD, RD, elevation)
PI	202	M-1	LN(HTG)=F(dss, ln_ht, height, sin_slpe, CCF, BAL, QMD, RD, elevation)
	202	M-1.1	LN(HTG)=F(dss, ln_ht, height, sin_slpe, cos_slpe, CCF, BA_HA, BAL, elevation, Shape, time)
	165	M-1.2	LN(HTG)=F(dss, ln_ht, height, sin_slpe, cos_slpe, CCF, BA_HA, QMD, RD, time, Shape, shrubs)
	202	M-2	HTG=EXP(dss, ln_ht, height, CCF)
	202	M-3	SQRT(HTG)=F(dss, ht_sq, height, sin_slpe, cos_slpe, CCF, BAL, QMD, RD)
Sx	216	M-1	LN(HTG)=F(dss, ln_ht, height, sl_ratio, sin_slpe, cos_slpe, CCF, BA_HA, BAL, QMD)
	216	M-1.1	LN(HTG)=F(dss, ln_ht, height, sl_ratio, sin_slpe, cos_slpe, CCF, BA_HA, BAL, QMD, Shape, time)
	162	M-1.2	LN(HTG)=F(dss, ln_ht, height, sin_slpe, cos_slpe, CCF, BA_HA, BAL, QMD, time, Shape, herbs)
	216	M-2	HTG=EXP(dss, ln_ht, height, sl_ratio, sin_slpe, BA_HA)
	216	M-3	SQRT(HTG)=F(dss, ln_ht, height, sl_ratio, sin_slpe, cos_slpe, CCF, BA_HA, BAL, QMD)

Table 3. Fit statistics for equations used for predicting small tree five-year height growth.

Species	n	Model	R ^{2*}	I ²	SEE(m)	Bias
Fd	882	M-1	.	0.2615	0.4366	0.122
	882	M-1.1	.	0.2798	0.4683	.
	675	M-1.2	.	0.5185	0.441	.
	882	M-2	0.3256	.	0.4489	0.002
	882	M-3	.	0.3075	0.4568	0.066
PI	202	M-1	.	0.2635	0.5621	0.118
	202	M-1.1	.	0.5308	0.451	.
	165	M-1.2	.	0.6739	0.4229	.
	202	M-2	0.3313	.	0.5258	-0.00014
	202	M-3	.	0.3292	0.5373	0.057
Sx	216	M-1	.	0.3465	0.4845	0.117
	216	M-1.1	.	0.3868	0.4681	.
	162	M-1.2	.	0.6403	0.427	.
	216	M-2	0.3582	.	0.4695	0.0016
	216	M-3	.	0.3915	0.4663	0.054

The original Prognosis NI performed poorly with the present data (Lencar and Marshall 2000). By refitting the model and retaining only the significant variables, a better solution was obtained (M-1, see Table 2 and 3). The I^2 values for model M-1 is comparable for Douglas-fir and lodgepole pine, but the SEE is lower for Douglas-fir. The I^2 values for spruce are higher than for the other two species, although the SEE is also higher.

Of the species analyzed, lodgepole pine seemed to be less affected by the site series or by the aspect, the rate of growth being almost similar across the whole range of sites for which data were collected. However, this conclusion should be taken cautiously, because the number of observations was less than 25 for some of the site series across the three biogeoclimatic subzones analysed.

Graphs of the residuals by species for model M-1 indicate that five-year height growth was underestimated on average. The variance of the residuals across the range appeared homogeneous (Figures 53 to 55).

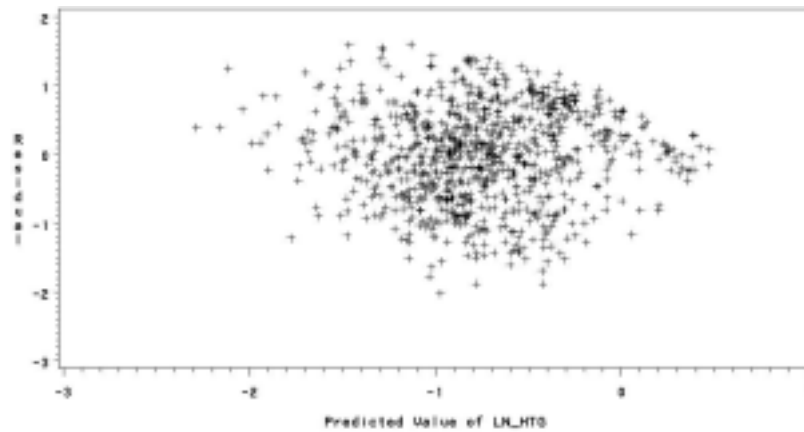


Figure 53. Plot of residuals from model M-1 for Douglas-fir.

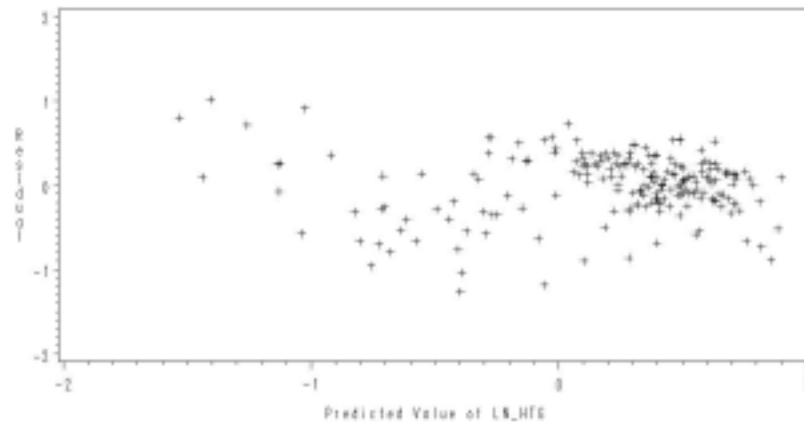


Figure 54. Plot of residuals from model M-1 for lodgepole pine.

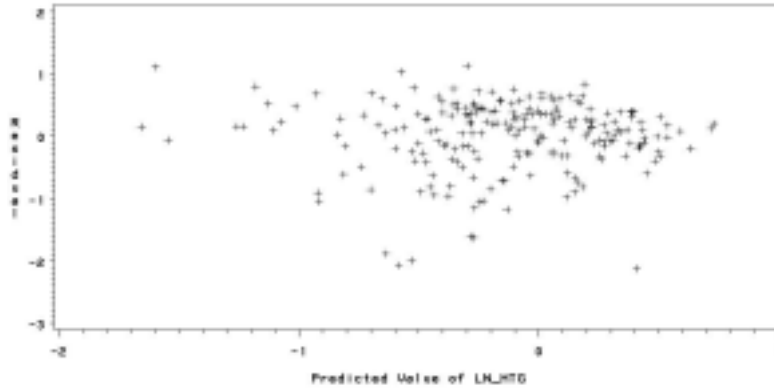


Figure 55. Plot of residuals from model M-1 for spruce.

The impact of including the time since disturbance to the basic model (model M-1.1) was more significant for lodgepole pine than for the other two species, with R^2 and SEE showing a dramatic improvement. Although the R^2 increased, so did the SEE for Douglas-fir under this model. By adding understory vegetation as a predicting variable (model M-1.2), a dramatic improvement was evident for all three species (Table 3). However, it should be noted that the number of observations available was less because these data were missing for IDF dk3.

Model 1 was used to determine the most significant variables to be used in an exponential model (Model 2). The parameters for the significant variables from Model 1 were used as input parameters using the NONLIN procedure from SAS. Not all the Model 1 parameters were significant in Model 2; those that were not significant were eliminated.

Overall, Model 2 yielded better results than Model 1 and was unbiased for all three species (Figures 56 to 58). Only the independent variables used in Prognosis NI were used; an improvement in the fit statistics should be achieved if additional variables were used. The residuals for Douglas-fir appear to show some heteroschedasticity for Douglas-fir. The Shapiro-Wilk test did not show significant deviation from normal.

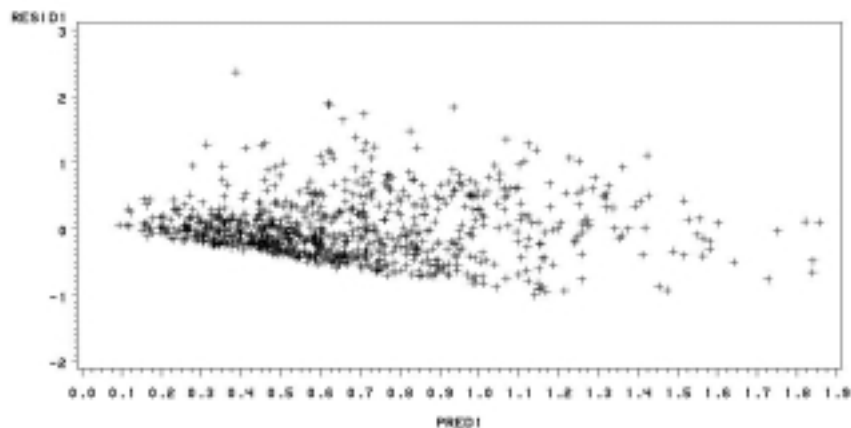


Figure 56. Plot of residuals from model M-2 for Douglas-fir.

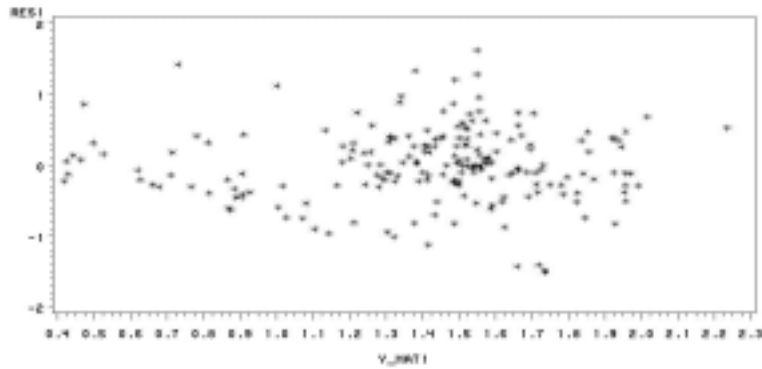


Figure 57. Plot of residuals from model M-2 for lodgepole pine.

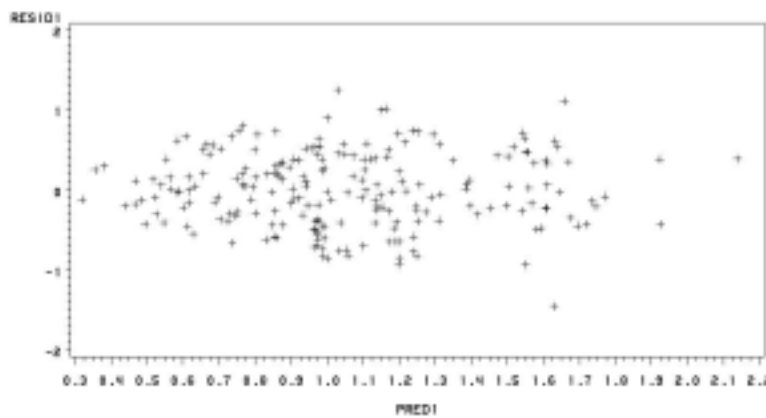


Figure 58. Plot of residuals from model M-2 for spruce.

Another attempt to model five-year height growth was made using the square root of the five-year height growth as a dependant variable (model M-3). Better results were obtained for all three species compared to the logarithmic model (model M-1), but not as good as the exponential model (model M-2). The results were less biased than those yielded by Model 1, but some heteroschedasticity was present for all three species (Figures 59 to 61).

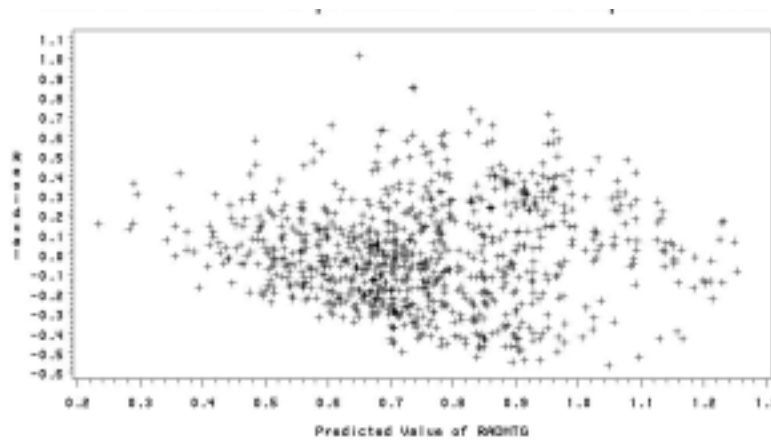


Figure 59. Plot of residuals from model M-3 for Douglas-fir.

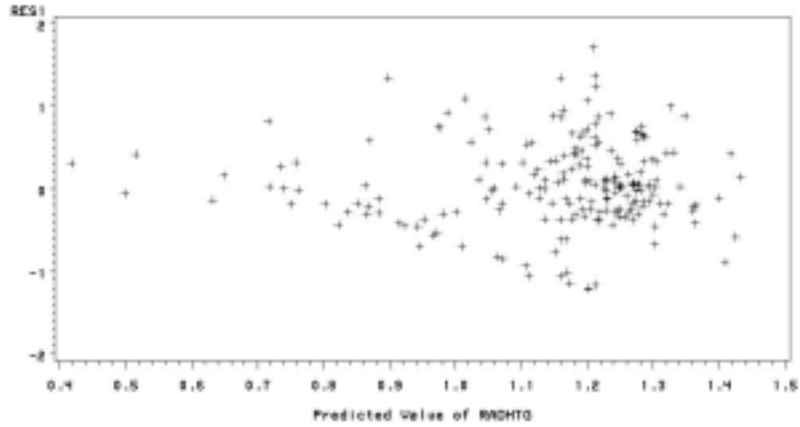


Figure 60. Plot of residuals from model M-3 for lodgepole pine.

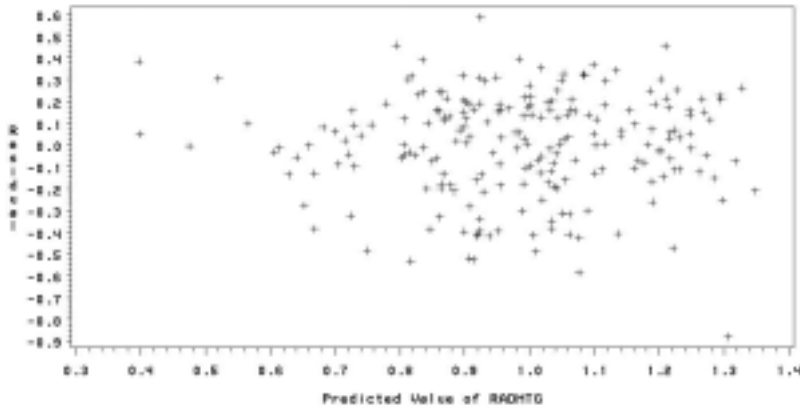


Figure 61. Plot of residuals from Model M-3 for spruce.

Coefficients for all models are presented in Appendix 1. Given the constraints of the Prognosis model with respect to the independent variables available, the best model found was the exponential form (model M-2), with insignificant bias and an acceptable SEE.

5.0 Summary

The small tree five-year height growth equation used in Prognosis NI was tested against the Kamloops and Williams Lake data. In all cases, the refitted equations or other tested model forms performed better than the Prognosis NI equation. The results varied with the equation.

An intrinsic drawback in the effort to calibrate small tree height growth is the model form itself. Prognosis uses a site classification system to represent site productivity; however, the factors that determine site productivity are difficult to measure (Monserud 1987). For the present project, an attempt was made to estimate the site index for the species analyzed by using the BEC site index classification system. This method is not very reliable. Although site index was a very significant predictor, but did not improve the model much over the original form.

From the summary statistics presented by Lencar and Marshall (2000), it is obvious that there was a trend in the average height growth of the three species analysed across site series. The trend indicated that the moister the site, the better the height growth. Despite this general trend, the difference in height growth among site series was not significant. This could be due to the fact that some site series did not have enough data.

In the Kamloops data, only three species (Douglas-fir, lodgepole pine, and spruce) had more than 25 observations of small tree height growth and only the mesic site series had more than 25 observations of small tree height growth for each of these species. No attempt was made to group site series into wider classes. However, even with grouping, some of the classes would not have enough measurements.

Improvements to the fit of the small tree five-year height growth equations could possibly be obtained if more data were available. Different equation forms could also yield better height predictions. Including other variables related to understory cover, site index and/or structural and density indices may prove beneficial.

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Appendix I – Model Coefficients

Regression Model-1 for dependant variable: LN_HTG

Species	FD	PL	SX	Existing data (Obs)		
Parameter				FD	PL	SX
Intercept	-0.2236	0.8624	-0.9532			
dk1_1	0.3748	-0.1362	-0.2073	84	64	32
dk1_2	0	0	0	10	0	0
dk1_3	-0.4245	-0.3047	0	51	7	0
dk1_4	0	0.0000	0	136	22	6
dk1_5	0.3018	0	-0.592	104	26	114
dk1_6	0.9152	0	-0.3633	5	1	8
dk2_1	0.1917	0	-0.608	58	21	8
dk2_3	0	0	0	35	0	0
dk2_4	0.2652	0.2328	0	39	16	4
dk2_5	0.6333	0.2319	0	29	12	2
dk2_6	1.0606	0	0	5	0	4
dk2_7	0.6513	0	0	5	0	0
dk3_1	0	0	-0.4011	270	29	30
dk3_2	0	0	0	0	0	0
dk3_3	0	0	0	4	2	0
dk3_5	0	0	-0.6384	24	0	2
dk3_6	0	0	0	8	0	0
dk3_7	0	0.4056	0	12	2	2
dk3_8	0	0	0	3	0	4
ln_ht	1.2755	0.9447	2.9572	882	202	216
height	-0.2765	-0.2234	-0.6273			
HTSQ	0	0	0			
sl_ratio	0.7777	0	-0.6322			
sin_slpe	0.2851	-0.4246	1.0037			
cos_slpe	-0.5365	0	-1.3195			
CCF	-0.0034	-0.0101	0.0052			
BA_HA	0	0	-0.0242			
BAL	-0.1937	-1.1001	-0.2913			
QMD	-0.0205	0.0299	0.0122			
RD	0	0.2482	0			
elevatn	-0.0004	-0.0008	0			
I ²	0.2615	0.2635	0.3465			
R ²	.	.	.			
SEE	0.4366	0.5621	0.4845			
BIAS	0.122	0.118	0.117			

Regression Model-2 for dependant variable: HTG-exponential form

Species	FD	PL	SX	Existing data (Obs)		
Parameter				FD	PL	SX
Intercept	-0.9428	0.0788	-1.0182			
dk1_1	0.2753	-0.2277	0	84	64	32
dk1_2	0	0	0	10	0	0
dk1_3	-0.3329	-0.6037	0	51	7	0
dk1_4	0	-0.2500	0	136	22	6
dk1_5	0.2104	0	-0.3627	104	26	114
dk1_6	0.6486	0	-0.2650	5	1	8
dk2_1	0.2468	0	0	58	21	8
dk2_3	0	0	0	35	0	0
dk2_4	0.4313	0	0	39	16	4
dk2_5	0.5127	0	0	29	12	2
dk2_6	0.8483	0	0	5	0	4
dk2_7	0.5009	0	0	5	0	0
dk3_1	0	0	-0.3640	270	29	30
dk3_2	0	0	0	0	0	0
dk3_3	0	0	0	4	2	0
dk3_5	0	0	0	24	0	2
dk3_6	0	0	0	8	0	0
dk3_7	0	0	0	12	2	2
dk3_8	0	0	0	3	0	4
ln_ht	2.0353	1.4255	3.0390	882	202	216
height	-0.4366	-0.3114	-0.6095			
sl_ratio	0.7969	0	-1.0069			
sin_slpe	0	0	0.7005			
cos_slpe	0	0	0			
CCF	-0.00339	-0.0039	0			
BA_HA	0	0	-0.0085			
BAL	-0.4472	0	0			
QMD	0	0	0			
RD	0	0	0			
elevatn	0	0	0			
I ²	.	.	.			
R ²	0.3256	0.3313	0.3582			
SEE	0.4489	0.5258	0.4695			
BIAS	0.002	-0.00014	0.0016			

Regression Model-3 for dependant variable: SQRTHTG

Species	FD	PL	SX	Existing data (Obs)		
Parameter				FD	PL	SX
Intercept	0.7809	1.0409	0.5717			
dk1_1	0.2722	-0.1256	0	84	64	32
dk1_2	0	0	0	10	0	0
dk1_3	0	-0.1913	0	51	7	0
dk1_4	0.1287	-0.0668	0	136	22	6
dk1_5	0.2416	0	-0.225	104	26	114
dk1_6	0.4903	0	-0.1431	5	1	8
dk2_1	0.2264	0	-0.2292	58	21	8
dk2_3	0.1892	0	0	35	0	0
dk2_4	0.2493	0.0751	0	39	16	4
dk2_5	0.3914	0	0	29	12	2
dk2_6	0.5404	0	0	5	0	4
dk2_7	0.3549	0	0	5	0	0
dk3_1	0.0471	0	-0.1467	270	29	30
dk3_2	0	0	0	0	0	0
dk3_3	0	0	0	4	2	0
dk3_5	0	0	-0.2689	24	0	2
dk3_6	0	0	0	8	0	0
dk3_7	0	0.1889	0	12	2	2
dk3_8	0	0	0	3	0	4
ln_ht	0.5139	0	1.2665	882	202	216
height	-0.1082	0.0919	-0.2617			
HTSQ	0	-0.0083	0			
sl_ratio	0.2776	0	-0.3104			
sin_slpe	0.1142	-0.206	0.5019			
cos_slpe	-0.1343	0.2414	-0.5565			
CCF	-0.0008	-0.0043	0.0021			
BA_HA	0	0	-0.0106			
BAL	-0.0755	-0.4792	-0.0842			
QMD	-0.009	0.0122	0.0049			
RD	-0.0141	0.0922	0			
elevatn	-0.0001	0	0			
I ²	0.3075	0.3292	0.3915			
R ²	.	.	.			
SEE	0.4568	0.5373	0.4663			
BIAS	0.066	0.057	0.054			

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