Small Tree Height Increment Models for Prognosis^{BC}, IDFdm2 Subzone Variant, Invermere Forest District

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EXECUTIVE SUMMARY

Accurate five year height increment predictions for small trees are an important prerequisite to effective predictions of stand growth and yield using the Prognosis^{BC} model. Fitting small tree height increment models for the Kootenay Dry Mild Interior Douglas-fir subzone variant (IDFdm2) of the Interior Douglas-fir (IDF) biogeoclimatic ecological classification zone is desirable in order to improve estimation for species within the Invermere Forest District.

Four base model forms were selected for regression analysis. Seven variables used in the current Prognosis^{BC} model were used for initial model fitting. For those species with very small sample sizes, a fifth model, using average five year height increment, was also assessed. Selected variables were then added, to determine whether their inclusion could improve the model fit.

Following initial model fitting, the data set was split, four times, into ¾ (model) and ¼ (test) data sets. Models were fit using the model data and variables determined in preliminary model fitting, then tested using the test data set. Fit statistics were calculated for both the model and test sets, for each of the four splits. These statistics were used to examine model performance. Final model fitting was completed using the full (pooled) data set for each species. Multiple coefficients of determination, standard errors of the estimate, biases, and biological reasoning were used to select preferred models for each species.

Base models produced poor to moderate fit statistics, and in some cases failed tests for normality and homoskedasticity. All of the fitted models were improved by the addition of variables not currently included in the Prognosis^{BC} small tree five year height increment models. Moisture class, UTM northing and elevation appeared most frequently in improved models. Interactions also appeared to be useful in improving predictive ability. Inclusion of these variables in future Prognosis^{BC} model fitting is recommended.

The standard errors of the estimate for the final models ranged from 0.290 to 0.390m. The two preferred models for the predominant species, Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) and lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), had standard errors of

the estimate of 0.371 and 0.343m and multiple coefficients of determination of 0.555 and 0.467, respectively.

Species with small data sets produced varied results. The hardwoods, paper birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.), were difficult to fit, which may relate to difficulty in sampling five year height increment in the field. Interior spruce (*Picea glauca x engelmannii*) models lacked measures of tree size. Western larch (*Larix occidentalis* Nutt.) models had very high fit statistics with very few variables, which data splitting indicated was not the result of overfitting. Ponderosa pine (*Pinus ponderosa* Laws.) models consistently included the same two measures of height, regardless of the variable of interest.

While data splitting was used to verify model performance, the test data used to assess model performance was not independent. Testing against independent data is recommended for all of the preferred models presented here.

With the exception of Douglas-fir and lodgepole pine, sample sizes were relatively small, reflecting their occurrence within the sampled areas. Additional sampling could be used to improve the models and increase the precision of prediction of five year height increment.

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1. INTRODUCTION

Prognosis^{BC} is a distance-independent tree growth model developed to predict the growth and yield of multi-species and multi-aged stands. Prognosis^{BC} forecasts future stand conditions based upon expected growth and mortality of individual trees in a stand (diameter growth, height increment, crown development, and mortality of individual trees). The model can simulate almost any form of harvesting, from partial cutting to clearcutting, and can simulate thinning from above, below, or by diameter class. The model has also been modified to simulate certain forest health events. Currently, Prognosis^{BC} does not predict regeneration establishment.

Prognosis^{BC} was adapted from the Forest Vegetation Simulator (FVS) model initiated by Stage (1973) in the USA. FVS was selected for use in the southeastern portion of British Columbia (BC) because of its ability to model multi-age, multi-species stands, similar to those commonly found in this area. Based on ecological similarities between northern Idaho and southeastern BC, the Northern Idaho (NI) variant of the Forest Vegetation Simulator was adapted to form the basis for Prognosis^{BC}. Initial examination of the five year height increment of trees with a diameter at breast height (DBH) of less than 7.5 cm showed that the small tree height increment model in the NI variant of FVS overestimated growth in BC stands (Boisvenue 1999).

The lack of viable small tree growth components limit applications of the existing version of this model. Several projects, including this one, have been initiated to model small tree height increment in areas of BC (*e.g.,* Boisvenue 1999, Lencar and Marshall 2000, Froese *et al.* 2001, and Hassani and Marshall 2001). The data from all of these projects were also combined to generate small tree height increment models fitted by biogeoclimatic zone (Temesgen 2002).

The purpose of this report is to present results of calibrating the Prognosis^{BC} small tree height increment model for the Kootenay Dry Mild Interior Douglas-fir subzone variant (IDFdm2) of the Interior Douglas-fir (IDF) biogeoclimatic ecological classification (BEC) zone in the Invermere Forest District, BC. Previous reports (Froese *et al.* 2001, Froese *et al.* 2002) summarize the full scope of the Prognosis^{BC} research in the Invermere IDFdm2 and present preliminary sampling results.

2. LITERATURE REVIEW

2.1. Factors Affecting Height Growth

At a given stage, the amount of height growth achieved by a tree is commonly though to rely on a combination of the tree's growth potential and growth-limiting factors. The growth potential of a tree relies on the interaction between its innate genetic characteristics and its growing environment (potential site productivity). Competition for resources is a major growth-limiting factor.

The combined attributes of a site describe the growing environment and competitive status that influences tree growth. However, not all of these factors are easy to observe and interpret, especially given their dynamic natures. Measurable variables may often reflect the combined effects of a number of site factors, rather than describing a single factor.

2.1.1. Measures of Size

Height

Height is an indication of the current stage of growth, which affects the rate of height increment. The rate of tree height growth is generally slow in the seedling stage, increases during the small tree or sapling stage, and then slows as the tree matures (Zedaker *et al.* 1987). As well, Williams *et al.* (1999) found that large saplings had larger height increments than small saplings. Height has been found to be a significant predictor variable in previous modelling efforts (*e.g.*, Wykoff 1986, Lencar and Marshall 2000, Temesgen 2002).

Diameter at Breast Height

Diameter at breast height is the diameter outside bark of a given tree, measured at 1.3m above the ground. Huang and Titus (1999) stated that larger diameter trees will theoretically be in a better competitive position, and therefore will have a greater height increment. Lencar and

Marshall (2000) found that the addition of DBH improved estimation of five year height increment.

2.1.2. Topographic Effects

Aspect

Aspect influences how much sunlight a site receives. South and southwest facing (exposed) slopes receive more sunlight and are therefore warmer, while north and northeast (protected) slopes receive less sunlight and are therefore cooler (Kabrick and Larsen 1999). Aspect may also affect soil properties, how soon snowpack melts from a given site, or how many growing degree days there are on the site. Stathers *et al.* (1990) stated that slope and aspect, combined, have a major influence on the amount of solar radiation a site receives.

Stage (1976) produced a method whereby the effects of aspect are transformed into a circular function. The affect of aspect is modified by slope: the effect of aspect will be higher on steeper slopes, while minimal slopes may be almost unaffected by changes in aspect. This procedure showed good results for modelling height yield of planted seedlings (Froese 2002) and has been used extensively in tree height increment modelling.

Slope

Slope interacts with aspect to impact light interception. It can also affect soil runoff and infiltration, and influence soil development, therefore influencing moisture status and nutrient availability (Zedaker *et al.* 1987).

Elevation

Elevation affects the number of growing degree days that are available to trees in a stand, frequency of late and early frosts, average temperatures, and is correlated with the amount of moisture a site receives. For a given location, the amount of moisture generally increases with increasing elevation (Stathers *et al.* 1990).

2.1.3. Location

Climate affects precipitation, solar radiation, air temperature and humidity, wind, and indirectly affects soil properties and thermal regimes (Stathers *et al.* 1990). Location information reflects regional and local variation, *i.e.*, the effects of climate modified by topography.

Easting

Easting is the UTM (Universal Transverse Mercator) coordinate of the plot centre. It is a measure of the location of the site from west to east. In the study area, sites to the west were generally located in the rainshadow and sites to the east were on the lee slopes. As such, easting is likely correlated to moisture status of the site and/or measures of aspect.

Northing

Northing is the UTM coordinate of the location of the site from north to south, which roughly parallels the Rocky Mountain Trench, running through the centre of the District. There is an observed difference in sites from north to south, reflected primarily in species composition; ponderosa pine (*Pinus ponderosa* Laws.) is found predominantly in the south, and interior spruce (*Picea glauca x engelmannii*) is more prevalent in the north. This geographic gradient may reflect differences in a number of factors, such as overall moisture status, site productivity, temperatures, and elevation. Northing may provide a good integrated measure of geographic variation, where the individual components producing this variation are not measurable.

2.1.4. Stand Density/Competitive Status

The competitive ability of a plant is determined by its ability to access available resources that are shared with its neighbours (Tremmel and Bazzaz 1995). Competitive indices incorporate factors that describe the tree's ability to exploit these resources (Dale *et al.* 1985). Measures of stand density and/or stand structure are often used to represent competitive effects of the surrounding stand. However, indices measure intensity of competition, regardless of how much stress that competition actually adds (Burton 1993).

Waring and Schlesinger (1985) stated that carbon resources are allocated to those parts of the plant that are most likely to increase the plant's chances for survival. Under stress, this could result in allocating resources to growth (either above or below ground) to try to optimize access to resources (Chen *et al.* 1996).

According to Waring and Schlesinger (1985), allocation varies depending upon the stressor. Moisture stress will inhibit shoot growth, and focus growth upon roots. Nutrient deficiencies may slow construction of photosynthetic enzymes in new foliage and thus slow canopy growth and shoot development, while again focusing development upon roots. Restricted light resources can either reduce height growth and increase lateral branch growth, in order to maximize light intercepted (shade tolerant species), or reduce lateral branch growth and emphasize height growth, in an attempt to "outgrow" the reduced light conditions (shade intolerant species) (Williams *et al.* 1999).

Height to Diameter Ratio

Height to diameter ratio (HDR) is calculated as the ratio of height (cm) divided by diameter (cm). HDR has been proposed as an individual tree-based competition index (Opio *et al.* 2000). A free growing tree should have a lower HDR than a tree limited by competitive stress (Mustard and Harper 1998, Williams *et al.* 1999).

Because shade intolerant species are more impacted by competition for light, they should have an overall higher HDR than more shade tolerant species grown under the same conditions. In fact this appears to be the case, as shown by Williams *et al.* (1999), where lodgepole pine pine (*Pinus contorta* var. *latifolia* Dougl.) HDRs ranged from 75 to 160 cm/cm in shade conditions, and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) HDRs ranged from 45 to 90 cm/cm (approximated values).

Basal Area (BA)

Basal area is the total basal area, in m^2/ha, of all small and large trees combined. This variable describes the competition provided by small and large trees, presumably for moisture and/or nutrients, since it does not incorporate measures of relative size. However, it does not describe the total competitive environment, since measures of regeneration, shrubs, and low vegetation are not included.

Quadratic Mean Diameter (QMD)

Quadratic mean diameter is the diameter of a tree with mean basal area. It is a function of both BA and the number of stems per hectare (Clutter *et al.* 1983). Given the same number of stems per hectare, variation in QMD indicates variation in the mean tree size, and vice versa As such, different stand structures could have similar QMD values.

Basal Area in Larger Trees (BAL/100)

Basal area in larger trees is defined as the total basal area of trees (m^2/ha) with a DBH larger than the subject tree. BAL100 is intended to describe the competitive status of a given tree (Wykoff 1990). This index assumes that competition is with larger trees, implying that competition is mainly for light resources.

Crown Competition Factor (CCF)

Crown competition factor is a unitless measure that again describes the total competition provided by small and large trees, in a slightly different manner. For a given tree, CCF is the sum of the maximum crown areas of trees represented by the tree in a unit area (ha), expressed as a % of that unit area. CCF represents the overall measure of stand density, taking into account differences in tree crown structure for different species (Wykoff 1990). The implication is that this variable has been modified to better represent competition for light.

Curtis' Relative Density (RD)

Curtis' relative density combines QMD and basal area to create a slightly different measure of density (Clutter *et al.* 1983). Not surprisingly, this index is very highly correlated to all other measures of density for all species in this study.

Stand Density Index (SDI)

Stand density index is a measure of stand density that relates to a predetermined relationship between the number of stems per hectare and the average tree size (Clutter *et al.* 1983). Again, this variable is very highly correlated with all other measures of stand density.

2.1.5. Management Effects

Harvesting affects residual stand structure, altering attributes such as access to light and/or protection by overstory, can have strong impacts upon soils and substrate, and affect many other attributes of the growing space.

Site Preparation

Site preparation can help alleviate frost and winter desiccation, cold soil temperatures, soil moisture, flooding, vegetative competition, animal damage, compacted soils and low aeration porosity (Eastham 1999). Froese and Marshall (1997) found that the effects of site preparation can influence height increment of trees above breast height in certain circumstances, either by reducing vegetative competition, soil/duff layer modification, and/or altering soil productivity.

Precommercial Silviculture

Stand tending treatments such as brushing, fertilization or application of herbicides can remove vegetative competition and alter the nutrient status of the site (Eastham 1999). Removal of competition may lead to increases in height growth, although some studies have indicated a lack of response to such treatments (Froese and Marshall 1997).

Presence of Organic Material

Some species grow better than others with the inclusion of organic material. For example, interior Douglas-fir is one of the conifers most sensitive to varying amounts of soil organic matter (Graham *et al.* 1990). Alteration in soil organic matter through harvesting activities or site preparation can therefore impact height growth of seedlings. How long this influence can last is unclear; Graham *et al.* (1990) and Froese and Marshall (1997) found evidence that the influence of site preparation lasted at least to the sapling stage.

Years Since Last Disturbance

Disturbance can alter the overstory stand composition, competitive relationships, and site productivity. Often, disturbance can result in "release" of understory trees from competitive restrictions, resulting in a change in their height growth patterns. For Douglas-fir and lodgepole pine, Kneeshaw *et al.* (2002) found that there was a 2-3 year delay before leader height growth responded to release. Following release growing space is made available for both advance and subsequent regeneration, but gradually new competitive restrictions are established.

2.1.6. Environmental Effects

Moisture

In general, moisture stress results in reduced tree growth. Lopushinski (1990) stated that the lack of soil moisture is a major factor in limiting transpiration in conifers in the interior. However, trees have different edaphic preferences for moisture which are reflected in different growth patterns. In addition, Williams *et al.* (1999) postulated that shade tolerance may be greater on drier sites.

2.1.7. Interactions

Moisture and Measures of Competition

Indices of competition are species and site specific (Burton 1993), and the “true” competition index of a given tree is never observable (Monserud and Ek 1977). All things held constant, the same value for an index of competition may have different meaning under different site conditions. Measures of stand density and competition have an increased importance where resources are more limiting. For example, in dry sites, which experience higher moisture stress, basal area of larger trees might have a stronger influence on height increment than on wetter sites.

Moisture and Aspect

Wetter sites may be more productive on exposed aspects, while drier sites may be more productive on protected aspects. Froese (2002) found significant interactions between Stage’s (1976) equation for aspect and moisture status when related to the height yield of planted seedlings.

Aspect and Elevation

The influence of exposed and protected sites may increase with increasing elevation. For example, Verbyla and Fisher (1989) found that mean site index of Ponderosa pine was lower on north-facing slopes than south-facing slopes at high elevations, but not significantly different at low elevation sites. Because higher elevation sites are generally colder, with fewer growing degree days, exposed sites may provide trees with an advantage, and may exhibit larger five year height increments. Protected sites may reduce the number of growing degree days, or experience more damaging frosts, reducing overall height increment.

2.2. Modelling Height Increment

Prognosis^{BC} is a tree growth model. Tree growth models project individual tree growth on an annual or periodic basis, and then aggregate these attributes to a stand level (Dale *et al.* 1985). Ritchie and Hann (1986) stated that height increment prediction is often the “weak link” of stand growth simulators. More work has been done on prediction of total height than height increment; often models predict future height from current height, rather than height increment itself (*e.g.*,, Cieszewski and Bella 1993), subtracting to obtain height increment. Alternatively, height increment equations can be obtained by taking the derivative of total height models. There are a number of height prediction model forms, many of which were summarized by Huang *et al.* (1992). Zeide (1993) provided a good summary of growth models in general.

Two approaches to modelling height increment have been identified by Huang and Titus (1999):

1. growth-potential independent approach: focuses on height increment as a function of tree and stand characteristics, including competitiveness of the tree within the stand; and
2. growth-potential dependant approach: first identifies the potential height growth for trees with no competitive influences, then provides a “competitive adjustment factor” to reduce (adjust) this potential.

Growth-potential dependant models often predict potential growth as a function of site index and age (*e.g.*, Monserud and Ek 1977, Hann and Ritchie 1988). Since site index is not a good measure for uneven aged stands, these methods are not appropriate for small tree height growth modelling in the IDFdm2.

An exception to this is the model developed by Huang and Titus (1999), which uses a site productivity index, determined by the height-diameter relationship between dominant and codominant trees. The model is based on the Box-Lucas function:

$$HI = \frac{\theta_1}{\theta_1 - \theta_2}(e^{-\theta_2 H} - e^{-\theta_1 H})$$

where HI is predicted height increment (m/y), H is total tree height (m), e is the base of the natural logarithm (2. 7182818) and θ_1 and θ_2 are parameters to be estimated.

There are also a number of growth-potential independent models, such as those developed for Prognosis^{BC}. Wykoff (1990) has referred to these are “composite models”, whereby tree, stand and site characteristics are incorporated into a single equation. The current small tree (five year) height increment model was developed by Temesgen (2002) and has been incorporated into the most recent version (3.0) of Prognosis^{BC}, yet to be released. The equation form is:

$$HTG = EXP[b_0 + b_1(SL \times COS(ASP)) + b_2(SL \times SIN(ASP)) + b_3 SL + b_4 HT + b_5 LN(HT) + b_6 CCF + b_7(\frac{BAL}{100})]$$

where HTG is predicted five year height increment (m), SL x COS(ASP) is the cosine of stand aspect (in radians) x slope (percent), SL x SIN(ASP) is the sine of stand aspect (in radians) x slope (percent), SL is stand slope ratio (percent slope/100), HT is total tree height (m), ln(HT) is the natural log of tree height (ln(m)), CCF is crown competition factor, BAL is basal area in larger trees (m^2/ha), EXP is the base of the natural logarithm (2. 7182818) and b_0 to b_7 are regression parameters which vary by tree species.

The North Idaho variant of the FVS model uses the model formulation presented in the Version 5 User’s Guide (Wykoff 1986). Height increment for trees less than 25.4 cm (10 inches) DBH (12.7 cm (5 inches) for lodgepole pine) is predicted according to the model:

$$\begin{aligned}\ln(HTG) = LOC + HAB + SPP + b_1\ln(HT) + b_2 CCF + b_3(SL \times \cos(ASP)) \\ + b_4(SL \times \sin(ASP)) + b_5 SL + b_6(BAL/100)\end{aligned}$$

where ln(HTG) is the predicted log of five year height increment (ft), LOC is a location-dependant constant, HAB is a habitat type-dependant constant, SPP is a species specific constant, ln(HT) is the natural log of tree height (ln(ft)), CCF is the crown competition factor, SL x cos(ASP) is the cosine of stand aspect (in radians) x slope (percent), SL x sin(ASP) is the sine of stand aspect (in radians) x slope (percent), SL is the stand slope ratio (percent slope/100), BAL is the basal area in larger trees (ft^2/acre), and b_1 to b_6 are regression parameters which vary by tree species.

This model form is similar to that recommended by Zeide (1993) as one of the most accurate basic model forms:

$$\ln(y') = k + p\ln(y) + qy$$

where y’ is the growth rate of the variable of interest (some measure of tree size), y is the tree size variable, and k, p and q are parameters to be estimated.

The Central Idaho variant uses a more complex model and is applied only to trees less than 12.7 cm (5 inches) DBH (Dixon 2000, pers. comm., cited in Froese and Robinson 2000):

$$\begin{aligned} HTG = {} & HAB + SPP + b_1(RELHT \times PTBA) + b_2 PTBAL + b_3 RELHT \\ & + b_4 CR + b_5 CR^2 + b_6 BA + b_7 BAL \end{aligned},$$

with:

$$RELHT = \frac{HT}{H40} \quad \{0 \le RELHT \le 1.5,$$

where HTG is the predicted five year height increment (ft), HAB is a habitat type-dependant constant, SPP is a species specific constant, RELHT is the height of the subject tree (HT) divided by the average height of the 40 largest trees in the stand (H40), PTBA is the point basal area (ft^2/acre), PTBAL is the point basal area in larger trees (ft^2/acre), CR is the crown ratio, CR^2 is the squared crown ratio, BA is the basal area (ft^2/acre), BAL is the basal area in larger trees (ft^2/acre), and b_1 through b_7 are species-specific parameter estimates.

Diameter growth increment models are generally not tied to site index or age, and so could be used as base models as well, modifying them for use as height increment models. Two examples are Leak and Graber (1976) and Vanclay (1995), respectively:

$$DI = b_0 + b_1 DBH + b_2 DBH^2 + b_3 BA + b_4 BA^2$$

and

$$\log(DI + 0.02) = b_0 + b_1 D + b_2 \log(D) + b_3 (S \times \log(D)) + b_4 \log(B) + b_5 BAL$$

where DI is the predicted diameter increment, DBH is the diameter at breast height, BA is the basal area, BAL is the basal area in larger trees, S is a binary variable indicating preferred soils, and b_0 through b5 are parameter estimates.

3. METHODS

3.1. Study Area

The IDF BEC zone occupies the rolling hills and valley terrain of the southern interior plateau of British Columbia (Hope *et al.* 1991). This zone accounts for approximately 5% of the British Columbian landscape (BC Ministry of Forests 1995), and is characterized by warm, dry summers and cool winters, with a relatively long growing season (Hope *et al.* 1991). Rainshadow effects are an important climatic factor. Climax stands are comprised mainly of Douglas-fir, either pure or mixed with other species.

Two variants of the IDF occur in the Invermere Forest District: the IDFun (Undifferentiated Interior Douglas-fir (Windermere Lake) Unit) and the IDFdm2 (Kootenay Dry Mild Interior Douglas-fir Variant). The IDFun occupies a small area that is mainly on private land (Braumandl *et al.* 1992), and was not targeted for Prognosis^{BC} calibration.

Within the Invermere Forest District, the IDFdm2 is located in the valley bottoms and lower slopes of the Rocky Mountain Trench, and in the valley bottoms of the major tributary rivers, such as the Findlay, Spillimacheen, and Kootenay Rivers (Braumandel *et al.* 1992). Douglas-fir is the dominant species, however Ponderosa pine, lodgepole pine, western larch (*Larix occidentalis* Nutt.) and interior (hybrid) spruce are also common. Other species occur infrequently. Table 1 provides a complete list of tree species, scientific names, and species codes referred to in this report.

The IDFdm2 ranges in elevation from 800 to 1200 m on south aspects, and from 800 to 1100 m on north aspects. This is an important area for cattle grazing and wildlife. The IDFdm2 generally extends into the Dry Cool Montane Spruce (MSdk) at higher elevations and the Dry Hot Ponderosa Pine (PPdh) at lower elevations. The extent of the IDFdm2 within the Invermere Forest District is illustrated in Figure 1.

Table 1. Local name, scientific name, and species code for trees of the IDFdm2.

Local Name	Scientific Name	Code
Douglas-fir	*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco	Fd
Interior spruce	*Picea glauca* (Moench) Voss *x Engelmannii* Parry	Sxw
Lodgepole pine	*Pinus contorta* var. *latifolia* Dougl.	Pl
Paper birch	*Betula papyrifera* Marsh.	Ep
Ponderosa pine	*Pinus ponderosa* Laws.	Py
Rocky Mountain Juniper	*Juniperus scopulorum* Sarg.	Rj
Subalpine fir	*Abies lasiocarpa* (Doug.) Lindl	Bl
Trembling aspen	*Populus tremuloides* Michx.	At
Western larch	*Larix occidentalis* Nutt.	Lw

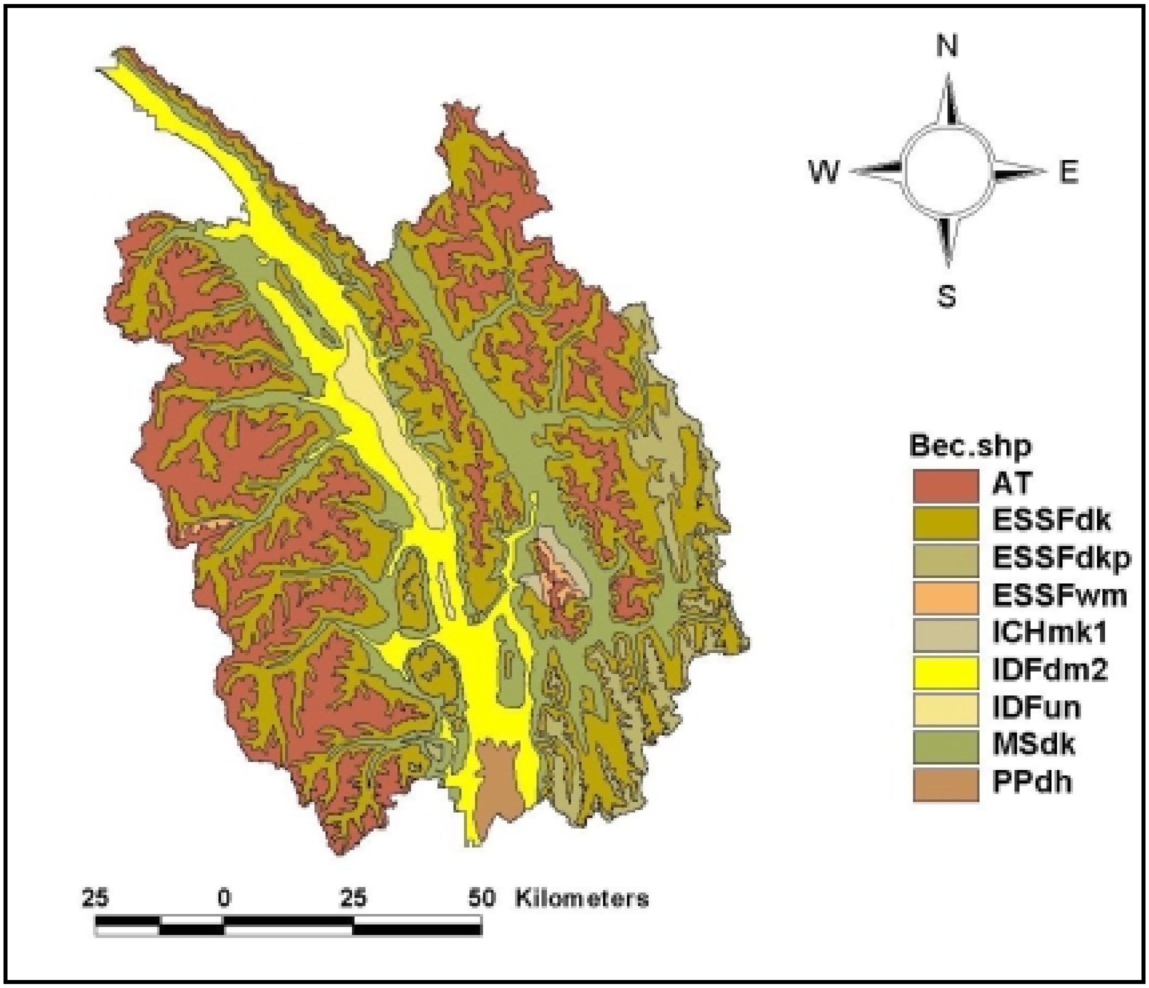

Figure 1. Location of biogeoclimatic variants within the Invermere Forest District

* AT = Alpine Tundra Zone; ESSFdk = Engelmann Spruce/Subalpine Fir Dry Cool Subzone; ESSFdkp = Engelmann Spruce/Subalpine Fir Dry Cool Parkland Subzone; ESSFwm = Engelmann Spruce/Subalpine Fir Wet Mild Subzone; ICHmk1 = Kootenay Moist Cool Interior Cedar Hemlock Variant; IDFdm2 = Kootenay Dry Mild Interior Douglas Fir Variant; IDFun = Undifferentiated Interior Douglas Fir Unit; MSdk = Dry Cool Montane Spruce Subzone; PPdh= Kettle Dry Hot Ponderosa Pine Variant

3.2. Field Sampling

Data collection procedures for small tree height increment and regeneration model calibration were initially designed by Boisvenue (1999), based upon methods originally outlined by Ferguson and Crookston (1991). Field sampling completed in subsequent years in southeastern BC (Lencar and Marshall 2000, Hassani and Marshall 2001) incorporated refinements to the design. The sampling strategy for the 2001 field season incorporated further refinements based on results from this research, as well as an additional, exploratory component, which involved spatial attribute and substrate measurements. Only the sampling related to small tree five year height increment modelling is outlined here; the full sampling design is summarized in Froese *et al.* (2001).

3.2.1. Sampling Frame and Site Selection

The sampling frame consisted of all areas located within the IDFdm2 biogeoclimatic subzone of the Rocky Mountain Trench, Invermere Forest District, which had been disturbed (harvested) within the last 5-25 years. In addition, undisturbed sites were also identified. Sites were included in the sampling frame regardless of ownership. Site selection was restricted to those sites located within a two hour driving radius of Invermere, BC, in order to minimize cost and maximize time efficiency. Sampling effort focused on selecting: 80% partially cut (shelterwood, seed tree, and selection silviculture systems), 10% undisturbed (selected purposively based on similarities in site characteristics to those in partially cut stands) and 10% clearcut stands.

A sampling matrix was set up to aid in selection of disturbed stands. The sampling matrix categorized openings based upon number of years since disturbance (years since dist.), silvicultural system, site series, and elevation. There were 256 matrix categories (combinations of year since disturbance, silvicultural system, BEC and elevation) based upon these classification criteria (Table 2). Data provided by the Ministry of Forests from their ISIS (Integrated Silviculture Information System) database was used to identify 333 candidate openings that were harvested within the last 5-25 years. Openings were removed from the candidate list if they were: 1) missing BEC site series, disturbance type, silvicultural system, or elevation; 2) less than four ha in size; or 3) marked as “burned” or “wildfire”.

Table 2. Number of available openings in the IDFdm2, Invermere Forest District, by elevation, site series, and harvesting system.

	SILVICULTURE SYSTEM																
	Clearcut/Patch				**Selection**				**Shelterwood**				**Seed Tree**				
Years Since Dist.	**Elevation**				**Elevation**				**Elevation**				**Elevation**				
Site Series	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	
5 to 10 (1991-1996)																	Total
02																	0
03		4									1						5
01	2	2	1		2	2	8	2	1	2	3		2			1	28
04			1			2				5				1			9
11 to 15 (1986-1990)																	
02																	0
03			1						1								2
01		1	5	2	8	4	6	3		2			2		5	4	42
04			1			2	1			1		1		1	1		8
16 to 20 (1981-1985)																	
02								1									1
03								1									1
01			6		10	12	11	4						3	4	4	54
04	1			1		2	3					1		2	3	2	15
21 to 25 (1976-1980)																	
02						1	2										3
03							3										3
01		2	2	1	3	7	17	4							1	1	38
04		1	6		1	5	5	4						1			23
Total	3	10	23	4	24	37	56	19	2	10	4	2	4	8	14	12	232

The remaining 232 openings were classified as potential sites for data collection, and were categorized into the sampling matrix (Table 2). These openings covered a range of 75 matrix categories. In order to sample as full a range of conditions as possible within the financial and time constraints, a maximum of one opening per available matrix category was selected for sampling.

Because the IDF runs north to south along the Rocky Mountain trench, a geographic [climatic] gradient from north to south was expected. In addition, the western side of the valley was generally on the lee slopes of the mountain ranges, and the eastern side was generally on the windward slopes. Therefore, in addition to ensuring that the appropriate polygons were selected based upon the sampling matrix criteria, selection was directed towards obtaining a range of geographic locations and aspects.

Each selected opening was assessed in the field as to suitability. Unsuitable openings were discarded and new openings were selected, and the sampling matrix was adjusted accordingly. In some cases, no suitable openings could be found within a given category.

Preliminary selection was by opening, since this is how the information was summarized in the ISIS database; however, sampling was based on polygons. Once an opening was selected, the number of polygons within the opening were determined. Where a single polygon existed, that polygon was sampled. Where there was more than one polygon, the largest polygon was selected for sampling. Where no single polygon was of an acceptable size (one that would allow a minimum of two plots to be sampled at 100m spacing, without being within 50m of adjacent opening boundaries), an alternate opening was selected.

Within selected polygons, plots were established using systematic sampling with a random start. The number of plots was based upon the degree of variability present and the size of the polygon, with a minimum of two plots per polygon. More variable (heterogeneous) polygons were sampled more intensively. Plots were established at a minimum distance of 50 m from roads or other openings, in order to avoid the effects of edge. Plots were established 100 m apart within the polygon. Sampled polygons are listed in Table 3.

Table 3. Selected openings in the IDFdm2, Invermere Forest District, by elevation, site series, and harvesting system.

	SILVICULTURE SYSTEM															
	Clearcut/Patch				**Selection**				**Shelterwood**				**Seed Tree**			
Years Since Dist.	**Elevation**				**Elevation**				**Elevation**				**Elevation**			
Site Series	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+
5 to 10 (1991-1996)																
02																
03											82K080/21					
01						82K060/46	82G092/121				82J022/60		82G092/124			
04			82K089/20							82J032/29				82J032/30		
11 to 15 (1986-1990)																
02																
03			82J002/18						82G092/106							
01						82J002/58				82K070/56			82K070/55	82G081/60		82K069/60
04							82K070/48			82K079/55					82K079/94	82K010/11
16 to 20 (1981-1985)																
02																
03																
01			82K069/56	82J012/28	82G071/52	82K070/27								82K069/52	82J022/28	82J012/33
04							82J012/16									
21 to 25 (1976-1980)																
02																
03							82J011/10									
01			82K079/21		82K070/03		82K020/40									
04								82K059/26								

3.2.2. Data Collection

Plot size was 11.28m (0.04 ha). All large and small trees within each plot were recorded. The location of each plot was recorded using a portable Geographic Position System (GPS) unit, and the following plot-level attributes were documented:

1. Mapsheet, opening number, polygon number, and plot number;
2. Latitude and longitude;
3. Aspect (degrees);
4. Slope angle (percent);
5. Slope position;
6. Elevation;
7. BEC site series and associated ecological factors (i.e. partial vegetation list);
8. Site preparation method (where identifiable);
9. Disturbance information (where available);
10. Disturbance year; and
11. Other information where deemed important (*e.g.*, grazing intensity).

Large trees were defined as those with a DBH greater than 7.5 cm. Species and DBH was recorded, in order to identify species composition in the overstory and to estimate retention level and residual basal area. Where numbers allowed, two trees from each species were randomly selected and measured for height. Tree health information (pests, pathogens, crooks, and so on) was recorded where present.

Small trees were defined as those with DBH values between 2.0 and 7.5 cm. Species and DBH were recorded for each tree. Where numbers allowed, five trees of each species were subsampled for total height and five year height increment. The five year height increment was measured starting five years prior to the end of the previous growing season, so that the same period of growth (five full seasons) was measured for each tree. Where possible, whorls were used to determine five year height increment. Where whorls could not be confidently counted (*e.g.,* for non-determinant species and for some determinant trees), the trees were felled for measurement, and then sectioned until the five year increment was reached. Additional tree health information was again recorded as necessary.

3.3. Variable Selection

The variables considered for inclusion in the five year height increment models are listed in Table 4. Because of sample size issues, the number of categorical variables included was limited. Therefore, moisture class was the only categorical class included. Dry moisture classes were defined as site series 03 and 03/01; mesic moisture classes were defined as site series 01/03, 01, and 01/04; and wet moisture classes were defined as site series 04/01, 04, and 04/05.

Some variables discussed in Section 2.1 were not included based on results of early data analysis and the need to reduce the number of predictor variables. For example, Easting was not significant in preliminary regression analysis and was therefore not considered.

Many calculated variables relating to stand structure and density, such as SDI, RD, QMD, BA, BAL100 and CCF were very highly correlated. Generally, correlations exceeded 0.95 and were significantly different from zero at α=0.05. Early regression work indicated generally only one of BAL100 and CCF, which were highly correlated, would be selected using stepwise selection, and that they were generally interchangeable. That is, removal of BAL100 would result in selection of CCF instead, and the fit statistics would be very similar. If, however, both variables were selected, they would each have a high associated variance inflation factor (VIF), indicating instability of parameter estimates (Neter *et al.* 1996). Removal of one of the two variables did not strongly impact the calculated fit statistics.

Because of this behaviour, SDI, and RD were not included as additional variables, since they were very strongly correlated to BA, BAL100 and CCF, and similar behaviour was expected. However, QMD had a lower overall correlation, generally around 0.70, and was therefore considered an appropriate variable to include, although VIFs were monitored during the process of variable selection.

Biologically speaking, most or all of the variables discussed interact. However including too many variables can result in model overfitting. Therefore, only a limited selection of interactions were selected, based on biologically-based reasoning.

Table 4. Variables used in regression analysis for small tree height increment.

VARIABLE	**DESCRIPTION**
Variables of Interest	
HTG	*five year height increment (m)*
LNHTG	*natural log of five year height increment*
SQRTHTG	*square root of five year height increment*
Tree Size/Shape	
HEIGHT	*total height (m)*
LNHEIGHT	*natural log of total height*
HTSQ	*total height squared*
SQRTHT	*square root of total height*
DBH	*diameter at breast height (cm)*
LNDBH	*natural log of diameter at breast height*
DBHSQ	*diameter at breast height squared*
LNDBH	*natural log of diameter at breast height*
SQRTDBH	*square root of diameter at breast height*
HDR	*height to diameter ratio(cm/m)*
Topographic Effects	
COSASPECT	*cosine of aspect(in radians) x percent slope*
SINASPECT	*sine of aspect(in radians) x percent slope*
SL	*percent slope*
ELEV	*elevation (m)*
ELEVSQ	*elevation squared*
ELEVBYCOS	*interaction between elevation and COSASPECT*
ELEVBYSIN	*interaction between elevation and SINASPECT*
Location	
NORTHING	*UTM northing (m)*
Competitive Status/Stand Structure	
CCF	*crown competition factor*
BA	*basal area of stand* (m^2)
BAL100	*basal area in larger trees/100* (m^2)
QMD	*quadratic mean diameter*
Management Effects	
YRSINCE	*number of years since harvest*
Environmental Effects	
MOISTCLASS1,MOISTCLASS2	*dummy variables to represent three moisture classes*
MOISTBYCOS1,MOISTBYCOS2	*interaction between moisture class and COSASPECT*
MOISTBYSIN1,MOISTBYSIN2	*interaction between moisture class and SINASPECT*
MOISTBYBA1,MOISTBYBA2	*interaction between moisture class and BA*

3.4. Model Selection

The Prognosis^{BC} model increments small trees until they reach a DBH of 7.5 cm, at which point they are “handed off” to the large tree height increment model. Because of this, only a small portion of the height growth trajectory is modelled. Therefore, more complicated models, such as Chapman-Richards function, are unnecessary for modelling small tree height increment.

Four model forms were selected for regression analysis, based on those discussed in Section 2.2. The seven variables used in the current PrognosisBC model (Temesgen 2002) were selected for fitting these models. These four "base" models are summarized in Table 5. For those models with very small sample sizes, a fifth model, using average five year height increment, was also assessed (Model 5). Selected variables were then added, to determine whether their inclusion could improve the model fit. These variables were: DBH (and transformations), HDR, ELEV, ELEVSQ, ELEVBYCOS, ELEVBYSIN, NORTHING, QMD, BA, YRSINCE, MOISTCLASS1, MOISTCLASS2, MOISTBYBA1, MOISTBYBA2, MOISTBYCOS1, MOISTBYCOS2, MOISTBYSIN1, and MOISTBYSIN2.

Table 5. Base models used in model fitting.

Form	Equation
1	$LNHTG = b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100$
2^*	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100)$
3	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100$
4	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100$
5	$HTG = b_0$

* where exp is the base of the natural logarithm (2. 7182818) and b^0 to b^7 are parameters to be estimated

3.5. Model Fitting

All data entry was completed in Microsoft® Excel 2000 (Microsoft Corporation 1985-1999). Data were reviewed to ensure that there were no entry errors. All analyses were completed using SAS™, version 8.02 (SAS Institute Inc. 1999-2001).

Correlations between continuous variables were assessed using PROC CORR to obtain Pearson's correlation coefficients. These were informally assessed to gain some idea of the relationship between five year height increment and other variables under consideration for each species.

Because each species has different growth behaviour, models were fit separately by species. Because of its very small sample size (n=10), no model was fit for subalpine fir. The four base models were fit first, then the additional variables were used to try to improve the model fit.

PROC REG was used for fitting linear and/or linearized models (Models 1, 3 and 4). Stepwise selection was used to determine which variables to include in the model. For small data sets, Rsquare selection was used to determine potential variable combinations which could provide the best results with the fewest number of variables. Combinations were selected preferentially, with emphasis placed on finding those combinations that included all of: an expression of tree size, competition, and site productivity. Variance inflation factors (VIFs) were examined to determine whether correlation between predictor variables could contribute to instability of parameter estimates. Neter *et al.* (1996) has stated that high variance inflation factors can result in parameter estimate instability. Where there were two variables with a VIF greater than 10, one was removed, and the model was reassessed to ensure that this did not greatly impact fit statistics. For species with small sample sizes, stepwise selection was used with caution, since selection of too many significant variables could lead to overfitting.

PROC NLIN was used to fit nonlinear models (Model 2). Results from fitting Model 1 using PROC REG were used to obtain starting values for parameters in Model 2. Variables were then removed one at a time, based on asymptotic confidence intervals (where the confidence interval included zero), and the model was reassessed. Variance inflation factors could not be obtained using PROC NLIN, therefore decisions on removing correlated variables were based on previous experience in fitting the other models and results from PROC CORR. Removal of a correlated predictor variable was followed by reassessment of the model, to ensure that fit statistics were not seriously altered.

For all procedures, if either COSASPECT or SINASPECT was included by the stepwise selection process, the selection process was rerun, using the INCLUDE command to force retention of both variables in order to maintain the biological function as described by Stage (1976). Similarly, if some expression of interaction with aspect was included, both were included, such as ELEVBYCOS and ELEVBYSIN.

Because MOISTCLASS1 and MOISTCLASS2 are dummy variables which, when combined, represent moisture classes (dry, medium, wet), if one was included in the model, the other was forced into the model as well. Interaction terms were also grouped together in a similar fashion. The exception to this is where a species occurred only in two moisture classes, such as trembling aspen. In such a case, MOISTCLASS1 and interactions with MOISTCLASS1 were admitted to the model singly.

Fit statistics were calculated for each model. For models which used the untransformed variable of interest HTG, the multiple coefficient of determination (R^2) was calculated for each model, using the formula:

$$R^2 = 1 - \frac{\Sigma(y_i - \hat{y}_i)^2}{\Sigma(y_i - \bar{y})^2}$$

Where y_i is the measured five year height increment, $\hat{y}_i$ is the predicted five year height increment, and $\bar{y}_i$ is the mean five year height increment.

In order to calculate the multiple coefficient of determination for transformed variables of interest (either log(HTG) or sqrt(HTG)), the predicted values were converted to HTG by taking either the inverse log or squaring, respectively. The resulting statistic is referred to as the I^2 value rather than the R^2 value, indicating that it has been transformed from its original units, and it calculated by:

$$I^2 = 1 - \frac{\Sigma(y_i - \hat{y}_i')^2}{\Sigma(y_i - \bar{y})^2}$$

Where y_i is the measured five year height increment, $\hat{y}_i'$ is the transformed (from log or square root units) predicted five year height increment, and $\bar{y}_i$ is the mean five year height increment.

For models which used the untransformed variable of interest HTG, the standard error of the estimate (SEE) was calculated for each model, using the formula:

$$SEE = \sqrt{\frac{\Sigma(y_i - \hat{y}_i)^2}{n - m - 1}}$$

Where y_i is the measured five year height increment, $\hat{y}_i$ is the predicted five year height increment, n is the number of observations and m is the number of predictor variables used.

The standard error of the estimate for transformed variables of interest (either log(HTG) or sqrt(HTG)), was calculated by again converting the predicted values by taking either the inverse log or squaring, respectively, and using the formula:

$$SEE' = \sqrt{\frac{\Sigma(y_i - \hat{y}_i')^2}{n - m - 1}}$$

Where y_i is the measured five year height increment, $\hat{y}_i'$ is in the original units (transformed from log or square root units) predicted five year height increment, n is the number of observations and m is the number of predictor variables used.

Bias was calculated using, for untransformed and transformed variables of interest, respectively:

$$Bias = \frac{\Sigma(y_i - \hat{y}_i)}{n} \text{ or } Bias' = \frac{\Sigma(y_i - \hat{y}_i')}{n}$$

Following initial model fitting, the data set was split, four times, into ¾ (model) and ¼ (test) data sets. Models were fit using the model data and variables determined in preliminary model fitting, then tested using the test data set. Fit statistics were calculated for both the model and test sets, for each of the four splits. These statistics were used to examine model performance. Poor model performance was noted if coefficients of multiple determination (R^2 or I^2 values), standard errors of the estimate (SEE or SEE'), or biases varied widely between model and test data sets, or between different split sets. Generally negative I^2 values, very high SEE' values, and very high or very low (negative) biases calculated from test sets indicated poor prediction accuracy. The full data set was used for the final fit of each model.

Because small sample sizes result in very small test data sets, they can provide unclear results. Therefore the data splitting procedure was limited to those species with large data sets: Douglas-fir and lodgepole pine.

Assumptions regarding the distribution of residuals were tested using PROC UNIVARIATE on the residuals. Normal probability plots and stem leaf histograms were used to visually assess whether the residuals were normally distributed. The Shapiro-Wilk test for normality was also used to test for normal distribution of residuals (α=0.05). Residual plots were examined for evidence of heteroskedasticity and autocorrelation, and to assess the aptness of the model form and variable selection.

Model selection was based on a combination of fit statistics, residuals, overall model performance and biological reasoning.

4. RESULTS

4.1. Douglas-fir

Table 6 provides the results of data splitting. For all of the models tested, results were generally consistent. The base models (Models 1, 2, 3 and 4) exhibited more variability in fit statistics based on test data. In particular, bias values of up to 20% and coefficients of multiple determination (I^2 values) as low as 0.101 were found. The improved models (Models 2a, 2b and 4a) showed more consistency and overall better fit statistics.

The four base models all provided relatively low multiple coefficients of determination (R^2 or I^2 values) and high standard errors of the estimate (SEE or SEE') (Table 7). R^2 or I^2 values ranged from 0.287 to 0.392, and SEE or SEE' ranged from 0.428 to 0.463m. Because they were based on transformed values of the response variable, Models 1 and 4 showed an overall bias (underprediction) for predicting five year height increment of 13.5% and 6.7%, respectively. Models 2 and 3 provided essentially zero bias. Model 1 showed evidence of nonnormality, and Model 3 exhibited some heteroskedasticity.

Stepwise selection resulted in very similar variable selection regardless of model form. Models 1, 2 and 3 all selected some expression of height (HEIGHT, LNHEIGHT, HTSQ, SQRTHT), influence of aspect (COSASPECT, SINASPECT), and some measure of stand density/competition (BAL100, CCF). Slope was selected for two of the models. Model 4 did not select any measure of size, and selected BAL100 rather than CCF.

Models 2a, 2b, and 4a provided the best improved models and these are included in Table 7. Model 2b does not include interaction terms. The models all provided improved R^2 or I^2 values and similar standard errors of the estimate. Model 4a, however, had an overall bias of 4.7%, while the other two models had essentially zero bias. Model 2a provided the highest coefficient of multiple determination (0.555), the lowest standard error of the estimate (0.371m), and the least model bias (0.001). It is therefore the preferred model. Estimated parameters for the model are provided in Appendix A.

Table 6. Fit statistics and summary data from data splitting, Douglas-fir.

		Fitting Data				Testing Data			
Model	Split	n	Bias or Bias’	R^2 or I^2	SEE or SEE’(m)	n	Bias or Bias’	R^2 or I^2	SEE or SEE’(m)
1	1	267	0.129	0.274	0.456	112	0.200	0.221	0.520
	2	298	0.137	0.251	0.478	81	0.055	0.462	0.401
	3	281	0.135	0.304	0.457	98	0.110	0.305	0.472
	4	291	0.136	0.328	0.458	88	0.143	0.101	0.499
	Full	379	0.135	0.287	0.463				
2	1	267	0.008	0.378	0.423	112	0.083	0.399	0.459
	2	298	0.006	0.349	0.446	81	-0.070	0.523	0.380
	3	281	0.008	0.408	0.422	98	-0.025	0.324	0.468
	4	291	0.010	0.449	0.416	88	0.021	0.139	0.491
	Full	379	0.008	0.392	0.428				
2a	1	267	0.002	0.549	0.368	112	0.036	0.541	0.422
	2	298	0.000	0.543	0.381	81	-0.042	0.542	0.400
	3	281	-0.001	0.543	0.378	98	-0.077	0.547	0.406
	4	291	0.003	0.616	0.353	88	0.049	0.280	0.480
	Full	379	0.001	0.555	0.371				
2b	1	267	0.009	0.529	0.372	112	0.049	0.488	0.434
	2	298	0.001	0.498	0.396	81	-0.035	0.587	0.366
	3	281	0.003	0.518	0.385	98	-0.060	0.515	0.408
	4	291	0.010	0.588	0.363	88	0.057	0.247	0.474
	Full	379	0.006	0.526	0.380				
3	1	267	0.000	0.315	0.444	112	0.058	0.325	0.486
	2	298	0.000	0.301	0.463	81	-0.073	0.387	0.431
	3	281	0.000	0.336	0.447	98	0.001	0.276	0.484
	4	291	0.000	0.357	0.449	88	0.008	0.191	0.477
	Full	379	0.000	0.325	0.451				
4	1	267	0.066	0.274	0.455	112	0.129	0.263	0.513
	2	298	0.067	0.270	0.470	81	-0.009	0.366	0.444
	3	281	0.068	0.291	0.460	98	0.057	0.291	0.484
	4	291	0.067	0.327	0.457	88	0.067	0.151	0.494
	Full	379	0.067	0.289	0.461				
4a	1	267	0.045	0.515	0.380	112	0.069	0.490	0.442
	2	298	0.046	0.523	0.388	81	0.009	0.534	0.401
	3	281	0.047	0.525	0.384	98	-0.026	0.508	0.420
	4	291	0.045	0.571	0.373	88	0.089	0.276	0.478
	Full	379	0.047	0.527	0.382				

n=number of trees

Table 7. Fit statistics and summary information for Douglas-fir models (n=379).
Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1*	$LNHTG = b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 CCF$	0.287	0.463	0.135
2	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF)$	0.392	0.428	0.008
2a	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 CCF + b_6 ELEVBYCOS$ $+ b_7 ELEVBYSIN + b_8 NORTHING + b_9 QMD + b_{10} YRSINCE + b_{11} MOISTCLASS\,1 + b_{12} MOISTCLASS\,2$ $+ b_{13} MOISTBYCOS\,1 + b_{14} MOISTBYCOS\,2 + b_{15} MOISTBYSIN\,1 + b_{16} MOISTBYSIN\,2)$	0.555	0.371	0.001
2b	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 SL + b_4 CCF + b_5 HDR + b_6 DBH$ $+ b_7 LNDBH + b_8 QMD + b_9 YRSINCE + b_{10} MOISTCLASS\,1 + b_{11} MOISTCLASS\,2)$	0.526	0.380	0.006
3**	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF$	0.325	0.451	0.000
4	$SQRTHTG = b_0 + b_1 COSASPECT + b_2 SINASPECT + b_3 BAL100$	0.289	0.460	0.067
4a	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 COSASPECT + b_4 SINASPECT + b_5 BAL100 + b_6 ELEVBYCOS$ $+ b_7 ELEVBYSIN + b_8 NORTHING + b_9 YRSINCE + b_{10} MOISTCLASS\;1 + b_{11} MOISTCLASS\;2 + b_{12} MOISTBYCOS\;1$ $+ b_{13} MOISTBYCOS\;2 + b_{14} MOISTBYSIN\;1 + b_{15} MOISTBYSIN\;2$	0.527	0.382	0.047

* model exhibits nonnormal distribution of residuals; ** model exhibits heteroskedasticity; n=number of trees

4.2. Interior spruce

All four base models had similar standard errors of the estimate, ranging from 0.322 to 0.344m (Table 8). R^2 or I^2 values ranged from 0.383 to 0.476. Models 1 and 4 had an overall bias (underprediction) of 6.5% and 3.4%, respectively. Model 2 showed evidence of a nonnormal distribution of residuals. The use of average five year height increment, Model 5, provided the poorest fit statistics, indicating that improvements in estimation can be obtained though the use of size, competition and site variables as predictors.

BAL100 was the sole variable selected for Models 1, 2 and 4, while Model 3 also included slope. The addition of moisture class (MOISTCLASS1, MOISTCLASS2) provided the best improvement in the fit statistics for the least number of added variables.

Models 3a and 4a (Table 8) provided the best improved models of those tested. Model 3a had the lowest standard error of the estimate (0.299 m), the highest coefficient of multiple determination (0.561), and no overall bias, and was therefore the preferred equation. Parameter estimates for the model are provided in Appendix A.

Table 8. Fit statistics and summary information for interior spruce models (n=38). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 BAL100$	0.383	0.344	0.065
2*	$HTG = \exp(b_0 + b_1 BAL100)$	0.418	0.334	-0.005
3	$HTG = b_0 + b_1 SL + b_2 BAL100$	0.476	0.322	0.000
3a	$HTG = b_0 + b_1 BAL100 + b_2 MOISTCLASS\ 1 + b_3 MOISTCLASS\ 2$	0.561	0.299	0.000
4	$SQRTHTG = b_0 + b_1 BAL100$	0.425	0.332	0.034
4a	$SQRTHTG = b_0 + b_1 BAL100 + b_2 MOISTCLASS\ 1 + b_3 MOISTCLASS\ 2$	0.553	0.301	0.028
5	$HTG = b_0$	0.000	0.432	0.000

* model exhibits nonnormal distribution of residuals; n=number of trees

4.3. Lodgepole pine

Table 9 provides the results of data splitting. The base models (Models 1, 2, 3 and 4) exhibited variability in fit statistics based on test data: all four base models had a negative I^2 value for split 4, indicating that the model fit did not adequate describe the variability within that test data set. However, the improved models (Models 2a, 2b, 4a and 4b) showed much more consistency overall, with no negative I^2 values and less variability in standard errors of the estimate and bias.

All four base models had very low R^2 or I^2 values, ranging from 0.129 to 0.173, and high standard errors of the estimate, ranging from 0.420 to 0.432m (Table 10). Models 1 and 4 had overall biases of 7.1% and 3.6%, respectively. Models 2 and 3 showed evidence of a nonnormal distribution of residuals.

Stepwise selection resulted in selection of similar variables for different model forms. All models included some measure of height and some indication of stand density/competition. Only Model 1 included measures relating to the influence of aspect.

Models 2a, 2b, 4a and 4b provided the best overall model improvements (Table 10). Models 2a and 4a are the result of stepwise selection including all additional variables mentioned in section 3.2. Models 2b and 4b did not include any interaction terms. Models 2a and 4a had essentially same variable selection, differing only in measures of height. Models 2b and 4b were similarly comparable.

Models 2a and 4a provided the highest coefficients of multiple determination, 0.467 and 0.470 respectively, and lowest standard errors of the estimate, both with 0.343m. Model 2a showed negligible bias, while model 4a exhibited an overall bias of 2.3% (underprediction). The lack of overall bias makes Model 2a the preferred model. Associated parameter estimates are summarized in Appendix A.

Table 9. Fit statistics and summary data from data splitting, lodgepole pine.

		Fitting Data				Testing Data			
Model	Split	n	Bias or Bias’	R^2 or I^2	SEE or SEE’(m)	n	Bias or Bias’	R^2 or I^2	SEE or SEE’(m)
1	1	151	0.068	0.128	0.426	52	0.127	0.096	0.481
	2	157	0.069	0.134	0.427	46	0.081	0.083	0.484
	3	151	0.077	0.075	0.450	52	0.087	0.270	0.402
	4	150	0.068	0.210	0.424	53	0.004	-0.312	0.498
	Full	203	0.071	0.129	0.432				
2	1	151	0.000	0.150	0.418	52	0.068	0.138	0.460
	2	157	0.000	0.146	0.421	46	0.019	0.171	0.450
	3	151	0.000	0.109	0.439	52	-0.001	0.265	0.395
	4	150	0.000	0.233	0.415	53	-0.060	-0.259	0.478
	Full	203	0.000	0.154	0.424				
2a	1	151	-0.001	0.472	0.337	52	-0.013	0.427	0.405
	2	157	0.000	0.505	0.328	46	0.059	0.223	0.476
	3	151	0.000	0.432	0.359	52	-0.009	0.543	0.337
	4	150	-0.001	0.496	0.345	53	-0.011	0.253	0.397
	Full	203	-0.001	0.467	0.343				
2b	1	151	-0.002	0.414	0.353	52	-0.049	0.343	0.424
	2	157	-0.002	0.419	0.353	46	0.103	0.315	0.435
	3	151	-0.002	0.375	0.374	52	-0.023	0.441	0.364
	4	150	-0.002	0.455	0.356	53	0.016	0.067	0.433
	Full	203	-0.002	0.404	0.360				
3	1	151	0.000	0.161	0.416	52	0.079	0.164	0.458
	2	157	0.000	0.170	0.417	46	0.021	0.176	0.454
	3	151	0.000	0.144	0.432	52	-0.009	0.249	0.403
	4	150	0.000	0.233	0.416	53	-0.086	-0.142	0.460
	Full	203	0.000	0.173	0.420				
4	1	151	0.035	0.155	0.418	52	0.111	0.128	0.488
	2	157	0.036	0.156	0.420	46	0.059	0.176	0.477
	3	151	0.038	0.132	0.435	52	0.024	0.258	0.419
	4	150	0.034	0.226	0.418	53	0.042	-0.149	0.481
	Full	203	0.036	0.163	0.423				
4a	1	151	0.021	0.475	0.337	52	0.006	0.332	0.443
	2	157	0.020	0.520	0.324	46	0.097	0.190	0.493
	3	151	0.025	0.434	0.360	52	-0.006	0.562	0.333
	4	150	0.022	0.507	0.342	53	0.016	0.188	0.418
	Full	203	0.023	0.470	0.343				
4b	1	151	0.023	0.416	0.353	52	-0.028	0.334	0.431
	2	157	0.023	0.455	0.343	46	0.133	0.272	0.454
	3	151	0.026	0.394	0.370	52	-0.015	0.486	0.353
	4	150	0.023	0.476	0.350	53	0.037	0.078	0.436
	Full	203	0.024	0.422	0.356				

n=number of trees

Table 10. Fit statistics and summary information for lodgepole pine models (n=203).
Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 LNHEIGHT + b_2 COSASPECT + b_3 SINASPECT + b_4 CCF)$	0.129	0.432	0.071
2^*	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 CCF)$	0.154	0.424	0.000
2a	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 BAL100 + b_3 ELEV + b_4 NORTHING + b_5 QMD$ $+ b_6 MOISTCLASS\ 1 + b_7 MOISTCLASS\ 2 + b_8 MOISTBYBA\ 1 + b_9 MOISTBYBA\ 2)$	0.467	0.343	-0.001
2b	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 BAL100 + b_3 ELEV + b_4 NORTHING + b_5 QMD$ $+ b_6 MOISTCLASS\ 1 + b_7 MOISTCLASS\ 2)$	0.404	0.360	-0.002
3^*	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 BAL100$	0.173	0.420	0.000
4	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 BAL100$	0.163	0.423	0.036
4a	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 BAL100 + b_4 ELEV + b_5 NORTHING + b_6 QMD$ $+ b_7 MOISTCLASS\ 1 + b_8 MOISTCLASS\ 2 + b_9 MOISTBYBA\ 1 + b_{10} MOISTBYBA\ 2$	0.470	0.343	0.023
4b	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 BAL100 + b_4 ELEV + b_5 NORTHING + b_6 QMD$ $+ b_7 MOISTCLASS\ 1 + b_8 MOISTCLASS\ 2$	0.422	0.356	0.024

* model exhibits nonnormal distribution of residuals; n=number of trees

4.4. Paper birch

All four base models had relatively high standard errors of the estimate, ranging from 0.448 to 0.484m (Table 11). R^2 or I^2 values ranged from 0.212 to 0.323. Models 1 and 4 had overall biases (underprediction) of 6.8% and 3.4%, respectively. The use of average five year height increment, Model 5, provided the poorest fit statistics.

Variables expressing the influence of aspect (COSASPECT and SINASPECT) and slope (SL) were selected for base Models 1, 3 and 4, while Model 2 fit with measures of height (HEIGHT, LNHEIGHT,) and slope. The addition of more variables using stepwise selection resulted in overfitting, so improved models were found using the Rsquare method (see Section 3.4.).

Models 3a and 4a (Table 11) provided the best improved models. Model 4a included a measure of tree size (SQRTDBH), while Model 3a relied on external factors (BAL100, ELEV, NORTHING). The preferred model, Model 4a, had the lowest standard error of the estimate (0.390m), the highest coefficient of multiple determination (0.489), and an overall bias of 2.5%. Estimated parameters for the model are provided in Appendix A.

Table 11. Fit statistics and summary information for paper birch models (n=32).
Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 COSASPECT + b_2 SINASPECT + b_3 SL$	0.212	0.484	0.068
2	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 SL)$	0.313	0.452	0.000
3	$HTG = b_0 + b_1 COSASPECT + b_2 SINASPECT + b_3 SL$	0.323	0.448	0.000
3a	$HTG = b_0 + b_1 BAL100 + b_2 ELEV + b_3 NORTHING$	0.486	0.391	0.000
4	$SQRTHTG = b_0 + b_1 COSASPECT + b_2 SINASPECT + b_3 SL$	0.285	0.461	0.034
4a	$SQRTHTG = b_0 + b_1 CCF + b_2 ELEV + b_3 SQRTDBH$	0.489	0.390	0.025
5	$HTG = b_0$	0.000	0.518	0.000

n=number of trees

4.5. Ponderosa pine

All four base models had similar R^2 or I^2 values, ranging from 0.462 to 0.480 (Table 12). Standard errors of the estimate ranged from 0.324 to 0.329m. Models 1 and 4 had an overall bias (underprediction) of 5.3% and 2.7%, respectively. Model 4 exhibited evidence of a nonnormal distribution of residuals. Model 5 provided the poorest fit statistics.

Both HEIGHT and CCF were consistently selected for each model, regardless of the variable of interest. NORTHING in Model 3a and MOISTBYBA1 to Model 4a improved fit statistics.

The multiple coefficients of determination for the models were similar for both models, at 0.519 and 0.522, respectively, for Models 3a and 4a. The standard errors of the estimate were also very similar, at 0.318 and 0.317m, respectively. Although Model 4a had an overall bias of 2.4% and slightly poorer fit statistics, it was selected as the preferred model due based on the parameter estimates. Model 3a had an intercept (b_0) of 37m, and relied mainly on the NORTHING value to reduce the predicted five year height increment. This had the potential for poor predictions outside of the modelled range of observations. Estimated parameters for the model are provided in Appendix A.

Table 12. Fit statistics and summary information for ponderosa pine models (n=28). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 HEIGHT + b_2 CCF$	0.462	0.329	0.053
2	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 CCF)$	0.480	0.324	0.000
3	$HTG = b_0 + b_1 HEIGHT + b_2 CCF$	0.469	0.327	0.000
3a	$HTG = b_0 + b_1 HEIGHT + b_2 CCF + b_3 NORTHING$	0.519	0.318	0.000
4*	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 CCF$	0.472	0.326	0.027
4a	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 CCF + b_3 MOISTBYBA1$	0.522	0.317	0.024
5	$HTG = b_0$	0.000	0.432	0.000

* model exhibits nonnormal distribution of residuals; n=number of trees

4.6. Trembling aspen

All four base models had low R^2 or I^2 values, ranging from 0.150 to 0.181 (Table 13). Standard errors of the estimate ranged from 0.368 to 0.385m. Models 1 and 4 had an overall bias (underprediction) of 4.3% and 2.3%, respectively. Models 2 and 3 showed evidence of nonormality of residuals. The use of average five year height increment, Model 5, provided the poorest fit statistics.

Selected variables were similar for each base model. All four models had some expression of height (LNHEIGHT, HEIGHT, or SQRTHT) and stand density/competition (BAL100, CCF). Model 1 also included the influence of aspect with COSASPECT and SINASPECT. The addition of more variables using stepwise selection resulted in overfitting, so the Rsquare option was used to select variable subsets for testing.

Models 3a and 3b (Table 13) provided the best improved models. Model 3b had the lowest standard error of the estimate (0.324m), the highest coefficient of multiple determination (0.378), and no overall bias and was therefore selected as the preferred model. Parameter estimates for the model are provided in Appendix A.

Table 13. Fit statistics and summary information for trembling aspen models (n=57). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 LNHEIGHT + b_2 COSASPECT + b_3 SINASPECT + b_4 BAL100$	0.137	0.385	0.043
2*	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 CCF)$	0.171	0.370	0.000
3*	$HTG = b_0 + b_1 HEIGHT + b_2 CCF$	0.181	0.368	0.000
3a	$HTG = b_0 + b_1 HEIGHT + b_2 CCF + b_3 MOISTCLASS1$	0.354	0.330	0.000
3b	$HTG = b_0 + b_1 HDR + b_2 YRSINCE + b_3 MOISTBYBA1$	0.378	0.324	0.000
4	$SQRTHTG = b_0 + b_1 SQRTHT + b_2 BAL100$	0.150	0.375	0.023
5	$HTG = b_0$	0.000	0.399	0.000

* model exhibits nonnormal distribution of residuals; n=number of trees

4.7. Western larch

All four base models had high multiple correlation coefficients, ranging from 0.673 to 0.849. Standard errors of the estimate were more variable, ranging from 0.290 to 0.415m (Table 14). Models 1 and 4 had overall biases of 5.0% and 1.2%, respectively. Model 1 showed evidence of a nonnormal distribution of residuals.

All four models had different variable selections. BAL100 was common to all four, while measures of height (HEIGHT, LNHEIGHT, HTSQ) were included in Models 2, 3 and 4. Measures of the influence of aspect (SINASPECT, COSASPECT) were included in Models 3 and 4.

No improvements of fit statistics were obtained. Addition of variables did not improve fit statistics without overfitting. Model 2 was selected as the preferred model since it had few variables, a high R^2 value (0.849), negligible bias, and the lowest standard error of the estimate (0.290m). Associated parameter estimates are summarized in Appendix A.

Table 14. Fit statistics and summary information for western larch models (n=43). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix A.

Model		R^2 or I^2	SEE or SEE'(m)	Bias or Bias'
1*	$LNHTG = b_0 + b_1 BAL100$	0.673	0.415	0.050
2	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 BAL100)$	0.849	0.290	0.003
3	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 COSASPECT + b_4 SINASPECT + b_5 BAL100$	0.832	0.313	0.000
4	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 COSASPECT + b_4 SINASPECT + b_5 BAL100$	0.852	0.294	0.012

* model exhibits nonnormal distribution of residuals; n=number of trees

5. DISCUSSION

Selected (preferred) models matched expectations based on biological reasoning. Lopushinsky (1990) stated that water deficits are the largest factors in reducing growth of interior Douglas-fir. Hermann and Lavender (1990) have stated that the proportion of Douglas-fir found in mixed-species stands depends on aspect, elevation, soil and history. The preferred model for Douglas-fir included a number of variables which relate to moisture, aspect and their interactions with elevation.

Lodgepole pine grows under a wide variety of ecological conditions, including wide variations in climatic temperatures. Armit (1966) stated that physiography, climate, soil and ecological factors rarely limit its growth, except in extreme situations. Lodgepole pine is resistant to frost injury, able to grow in very nutrient poor sites and sites with extreme water conditions (Klinka *et al.* 1989). However, lodgepole pine is very intolerant of shade and competition (Armit 1966). Many of the variables included in the preferred model form related to various environmental factors, but the interaction between moisture and basal area was significant only for this species, indicating the relative importance of competition.

Paper birch is adapted to cold climates and tolerates wide variations in soils, topography, rainfall, however it rarely grows where average July temperatures exceed 21°C and is very shade intolerant (Safford *et al.* 1990). The preferred model for paper birch included CCF, SQRTDBH and ELEV, which makes biological sense. Increasing elevation results in decreasing air temperatures, and since the IDF is generally very warm in the summer, may enhance the ability of paper birch to persist. CCF is a competition index which relates to the amount of competition for light.

Trembling aspen is tolerant of many environmental factors. Chen *et al.* (2002) found that latitude, longitude, elevation, aspect, moisture and nutrient regimes all had an affect on aspen site index. Trembling aspen is limited by temperatures (maximum mean July temperatures of 24°C), precipitation (occurs only in areas of water surplus), and competition (Perala 1990). It is a very shade intolerant species. The preferred model includes a competition index (HDR), and a measure of moisture (MOISTBYBA1) as it interacts with basal area, both biologically feasible variables.

The hardwoods were particularly difficult to fit, especially given their small sample size. Given the difficulty of distinguishing rings in hardwoods during destructive sampling, some of the variability in the data set is very likely due to measurement error, increasing the difficulty in modelling.

Western larch is a particularly interesting species, where very high multiple coefficients of determination and low standard errors of the estimate were obtained with very few variables. Given the small sample size, one might suspect overfitting of the model; however, informal data splitting showed that results were consistent between model and test data sets, even with very small numbers in the test data sets. This indicates low variability in five year height increment. This may be due to where larch occurs; if it is planted in very specific circumstances, such as higher elevations, lower basal area retentions and on wetter sites, then growth rates will be very similar. The other explanation could be that larch has very consistent growth rates regardless of outside influences. In either case, further sampling could potentially result in very precise estimates of western larch five year height increment for this area.

The usefulness of data splitting is illustrated in the results for lodgepole pine. Since sample size was relatively large, the initial variability in fit statistics from test data sets (including negative I^2 values) would indicate that the base models did not adequately describe the variability within the data set. Since the addition of new variables resulted in much more consistent results, it is evident that additional variables are needed to model five year height increment for lodgepole pine.

The inclusion of additional variables greatly improved the fit statistics for most of the models. Interactions also improved the fit (i.e. residual patterns and tests of normality) of the models over many of the base models. The use of the Rsquare method to create and compare variable combinations was very helpful in modelling species with small sample sizes, particularly where the number of variables needed to be limited in order to avoid overfitting. An increase in the sample size for those species with small data sets would allow the inclusion of more variables, which would likely improve the precision of the estimates. For example, the selected model for interior spruce relies solely on basal area in larger trees and moisture class to predict five year height increment.

While including some measure of competition was important to the modelling process, generally only a single measure was required. Because BA, BAL100 and CCF were highly correlated (generally 0.95 or greater), they explained an almost identical amount of variation in the data sets, and were essentially interchangeable. Because of their high correlation, inclusion of both variables provided very little increase in the explanatory power of the models, and led to high variance inflation factors, potentially contributing to parameter estimate instability. Other, less correlated variables such as QMD and HDR occasionally improved model fit statistics.

6. CONCLUSIONS

All of the fitted models were improved by the addition of variables not currently included in Prognosis^{BC} small tree five year height increment models. Moisture class, UTM northing and elevation appeared most frequently in improved models. Interactions also appeared to be useful in improving predictive ability. Inclusion of these variables in future Prognosis^{BC} model fitting is recommended.

The best test of a model's performance is to test it against independent data (Wykoff 1990). While data splitting was used to infer model performance, the test data used to assess performance was not independent. Testing against independent data is recommended for all of the preferred models presented here.

With the exception of Douglas-fir and lodgepole pine, sample sizes were relatively small, reflecting their occurrence within the sampled areas. Additional sampling could be used to improve the models and increase the precision of prediction of five year height increment.

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APPENDIX A. PARAMETER ESTIMATES FOR SELECTED MODELS

A.1. Parameter estimates for Douglas-fir

$$\begin{aligned}HTG = \exp(&b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 CCF + b_6 ELEVBYCOS \\ &+ b_7 ELEVBYSIN + b_8 NORTHING + b_9 QMD + b_{10} YRSINCE + b_{11} MOISTCLASS1 + b_{12} MOISTCLASS2 \\ &+ b_{13} MOISTBYCOS1 + b_{14} MOISTBYCOS2 + b_{15} MOISTBYSIN1 + b_{16} MOISTBYSIN2)\end{aligned}$$

Variable	Parameter Estimate
Intercept	11.5636
HEIGHT	-0.5120
LNHEIGHT	2.1963
COSASPECT	4.6660
SINASPECT	10.3350
CCF	-0.00654
ELEVBYCOS	-0.00576
ELEVBYSIN	-0.00945
NORTHING	-2.31E-6
QMD	-0.0188
YRSINCE	0.0238
MOISTCLASS1	0.7266
MOISTCLASS2	0.5040
MOISTBYCOS1	2.7290
MOISTBYCOS2	2.0608
MOISTBYSIN1	1.0447
MOISTBYSIN2	-1.4935

A.2. Parameter estimates for interior spruce

$$\boxed{HTG = b_0 + b_1 BAL100 + b_2 MOISTCLASS\,1 + b_3 MOISTCLASS\,2}$$

Variable	Parameter Estimate
Intercept	0.78463
BAL100	-2.81086
MOISTCLASS1	0.58843
MOISTCLASS2	0.39782

A.3. Parameter estimates for lodgepole pine

$$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 BAL100 + b_3 ELEV + b_4 NORTHING + b_5 QMD \\ + b_6 MOISTCLASS\ 1 + b_7 MOISTCLASS\ 2 + b_8 MOISTBYBA\ 1 + b_9 MOISTBYBA\ 2)$$

Variable	Parameter Estimate
Intercept	11.5074
LNHEIGHT	0.3457
BAL100	-5.1311
ELEV	-0.00069
NORTHING	-1.97E-6
QMD	0.0244
MOISTCLASS1	0.3519
MOISTCLASS2	0.1951
MOISTBYBA1	0.0343
MOISTBYBA2	0.00491

A.4. Parameter estimates for paper birch

$$\boxed{SQRTHTG = b_0 + b_1 CCF + b_2 ELEV + b_3 SQRTDBH}$$

Variable	Parameter Estimate
Intercept	2.58101
CCF	0.00332
ELEV	-0.00187
SQRTDBH	0.23886

A.5. Parameter estimates for ponderosa pine

$$\boxed{SQRTHTG = b_0 + b_1 HEIGHT + b_2 CCF + b_3 MOISTBYBA1}$$

Variable	Parameter Estimate
Intercept	0.86277
HEIGHT	0.14431
CCF	-0.00634
MOISTBYBA1	0.00886

A.6. Parameter estimates for trembling aspen

$$\boxed{HTG = b_0 + b_1 HDR + b_2 YRSINCE + b_3 MOISTBYBA1}$$

Variable	Parameter Estimate
Intercept	1.55449
HDR	0.00492
YRSINCE	-0.03711
MOISTBYBA1	-0.02490

A.7. Parameter estimates for western larch

$$\boxed{HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 BAL100)}$$

Variable	Parameter Estimate
Intercept	-0.1791
HEIGHT	-0.4817
LNHEIGHT	2.3077
BAL100	-5.0556