## Modelling Juvenile Height in Mixed Species, Even Aged Interior Cedar-Hemlock Stands

by

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## ABSTRACT

Height models for juvenile even aged mixed-species stands were developed for locations near Nelson, British Columbia. Separate models were developed for each conifer species found, as well as for paper birch (*Betula papyrifera*). The objectives were to develop models for: 1) the number of years to reach breast height; 2) height achieved at a given age above breast height (height yield); 3) separate models for all trees (average height) and the largest diameter dominant tree free of damage or suppression on a 0.01 ha plot (top height); and, 4) site and stand attributes incorporated as independent variables.

Numerous biophysical variables were tested as predictors of juvenile height. Statistically significant models for years to breast height and for height yield were developed for most species; most using variables other than site index. For modelling height yield, two *ad hoc* methods for including independent variables were used. For trees with multiple measurements *ad hoc* models were contrasted with a two-stage parameter prediction approach. The best *ad hoc* models used functions of site index; however, the parameter prediction approach produced models with equal or better fit to the best *ad hoc* models, including those using site index alone.

Few consistent trends in model form were observed for both years to breast height and height yield, and many models were not biologically tenable and should not be applied operationally. Because all combinations of independent variables were not equally sampled, the data may have not been sufficient to capture trends or variables may be acting as analogues for other causal factors. Regardless, the measured variables were useful predictors of juvenile height, even with small data sets. This promising result demonstrated the validity of the approach and the potential for precise height models not based on site index.

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## 1. INTRODUCTION

"Goodness of management can only be judged in specific cases by comparing what is done on-the-ground against what is needed in a particular forest to achieve the desired goals"

- Gordon Baskerville

### 1.1 BACKGROUND

Knowledge of early tree and stand height development is important for a variety of reasons. Many systems of site quality assessment, for timber and other resources, are linked to tree height yield<sup>1</sup>. Predicting future tree and stand height is important in planning and predicting the development of timber resources, and for the scheduling of harvest and silvicultural treatments, at the stand and forest level. Scheduling of treatments and estimation of timber yield<sup>2</sup> are directly related to stand development. Accurate assessment of future height is important for the appropriate use and development of many models of stand dynamics. Understanding height dynamics is important to ensure the use of models and development of plans for timber and non-timber resources are in the appropriate context. Furthermore, greater understanding of the processes that govern both tree and stand height dynamics will allow the development of better models.

Aside from the obvious impacts on the assessment of timber yield, stand height is important in forecasting the yield of non-timber resources. Values such as visual quality, wildlife habitat, recreation potential and hydrologic regime, to name a few, are strongly tied to the development of the stand canopy (Ministry of Forests 1993). These values, and biological diversity in particular, are often strongly tied to stand structure as well as height, because of the significant vertical stratification provided by forests (Hunter 1990). This is perhaps more important in mixed-species stands, for they often result in greater vertical stratification than pure-species stands (Oliver and Larson 1996).

## **1.2 RATIONALE FOR THIS RESEARCH**

There are two main impetuses for this research: one applied, and one more basic. Both relate to the important role that tree and stand height play in the development of tree, stand and forest-level values.

<sup>&</sup>lt;sup>1</sup> The phrase 'height yield' is used deliberately instead of 'height' or 'height growth' because the focus of this research is on the relationship between height produced with tree or stand age, not height alone or the rate of change in height (height growth).

<sup>&</sup>lt;sup>2</sup> In a forest management context, yield is usually used to represent the production of timber volume. However, the term is well suited to illustrate the production of other resources. For the purposes of this research, 'yield' will refer to the production of any resource in the context of the discussion.

## 1.2.1 Applied

In British Columbia (B.C.), many non-timber resources are managed by constraining the rate of cut such that a minimum amount and pattern of stand structures is maintained within a planning unit. So called 'greenup' and maximum disturbance requirements are examples, and they are commonly defined as the achievement of a critical height in a regenerating stand. These constraints can place substantial limitations on allowable annual harvest levels where the rate of height growth is not sufficient to alleviate one or more cover constraints. For example, in the Kootenay Timber Supply Area (TSA), past management was predicated on a three-pass harvest system – meaning all stands under management would be removed in one of three cycles of harvest. However, timber supply analyses have indicated that a change to a four or five pass harvest system, throughout the TSA, may be required to accommodate cover requirements (Ministry of Forests 1993). Sensitivity analyses suggest that this would necessitate a 5 or 19 percent reduction in allowable cut, respectively (Pedersen 1995).

Issues in tree and stand height dynamics contribute to this uncertainty in two ways. First, guidelines exist to define critical heights associated with non-timber values. For example, in the Kootenay Lake TSA, deer winter range is accommodated by limiting the amount of area within a planning unit less than 20 years of age and less than 46 years of age. These ages are associated with stand heights that are believed to meet habitat requirements for deer. However, this association has been made using a height yield relationship simply approximated across all sites from silviculture records (Ministry of Forests 1993). Tools that assist in more precisely predicting when a given stand achieves these critical height levels would be extremely valuable in reducing uncertainty around timber supply. Second, the association of wildlife habitat or other values with height is extremely coarse, at present. Patterns of height within stands vary widely with species composition and distribution, density, site quality, and age. The suitability of a given stand for habitat may vary equally widely. As management becomes more sophisticated, more complex tools to assess, describe and predict height development as well as other stand structures will become important.

Current height models are designed to predict top height<sup>3</sup>, or the height of a subset of trees that are believed the tallest in a given area. However, the yield of many non-timber resources may be far more closely related to stand structures than top heights. Getting around this by relating yield to top height at the stand level may be straightforward in single species, even-aged stands. In these stands, much knowledge exists about their dynamics, and the number of possible stand types is reasonable. In mixed species stands, the number of possible combinations likely makes this approach impossible.

Exactly how the yield of non-timber resources relates to height yield patterns in mixed-species stands is beyond the scope of this research. However, an initial approach to considering the

<sup>&</sup>lt;sup>3</sup> The definition of top height according to the Forest Productivity Council of British Columbia (June 1998) is "the height of the largest diameter tree on a 0.01 ha plot, providing the tree is suitable.

variability in tree height yield in mixed species stands may be to consider the average, rather than the top-height development for a given species. As long as the use of such models is constrained to larger scale averages, such models may be more reliable for managing non-timber resources. Furthermore, the consideration of height development with respect to stand structure may provide additional information for use in forecasting stand structure elsewhere.

## 1.2.2 Basic

The influence of height dynamics on administrative issues in management is of great concern to forest managers and to communities that rely on the forest industry. However, for many values other than timber production, what actually develops in the forest is of far greater importance. The actual impact of management on the yield of forest values depends on a reliable linkage between silvicultural practices, the resulting stand structures, the pattern of forest stands, and the values associated with them. Without this linkage, "management cannot be designed, nor can its effectiveness be determined" (Baskerville 1988). The use of a simple approximation of height yield relationships in forest level planning the Kootenay TSA (Ministry of Forests 1993), across all ranges of site quality, stand composition, silvicultural treatment, and geographic location to ensure the supply of deer winter range is a good example of a poor linkage.

Most research in stand and forest dynamics and yield has focussed on single-species. Examples are:

- the oft-cited European work of Assman (1970);
- the focus of textbooks on forest management, such as Clutter et al. (1983);
- a large number of initial spacing (espacement) and thinning trials (Froese and Marshall 1997); and,
- the popularity of maximum size / density theories of single-species population dynamics (the <sup>3</sup>/<sub>2</sub> power law White and Harper 1970; Drew and Flewelling 1977).

This research has been extremely useful, both in the development of models of timber yield (*e.g.*, Mitchell 1975) and in silvicultural decision making tools, like stand density management diagrams (*e.g.*, Farnden 1996).

However, many of the concepts developed and tested in single-species stands transfer poorly to mixed-species cases. For example, concepts of differentiation into crown classes in pure stands are complicated in mixed-species conditions, where one species has a greater tolerance of shade (Cobb 1988). The result is a wide variety of patterns of dominance, suppression and mortality that depend on species composition, site quality, spatial and temporal patterns of regeneration, and even geographic location (Oliver and Larson 1996). Over the last few decades there has been an increasing recognition of the limitations of the pure-species emphasis. In part, this is due to:

 Acknowledgment of the actual rarity of relatively pure-species stands, especially in some biogeoclimatic (BEC) zones, such as the interior cedar-hemlock (ICH) zone (Braumandl and Curran 1992) in British Columbia;

- Increasing interest in variable-retention silvicultural systems and natural regeneration;
- The desire to reduce uncertainty in forecasts of timber yield and in stand responses to silvicultural treatment; and,
- Increasing emphasis on non-timber objectives in forest management that are tied to stand structure and composition.

A greater emphasis on research and modelling of mixed-species dynamics has been the result (*e.g.*, Cobb 1988; Vanclay 1994; Cameron 1996; Oliver and Larson 1996). However, the level of knowledge of mixed-species stand dynamics, especially in western North America, continues to be disproportionate to the abundance and importance of mixed stands in management. Our knowledge would be especially enhanced in two ways:

- 1. through greater understanding of the response of juvenile height development to site and silvicultural variables between species commonly growing together; and,
- 2. with greater understanding of the relative differences in inherent height yield, knowledge of silvics can be extended to emergent patterns observed in mixed stands.

## **1.3 RESEARCH OBJECTIVES AND HYPOTHESES**

This research is intended to provide new information to address applied management needs for juvenile height models of trees commonly found in complex, mixed-species stands in the ICH BEC zone near Nelson, B.C. (the "Nelson Region"). Concurrently, this research will test alternative methods for modelling juvenile height and explore relationships with site and stand variables to enhance current understanding of basic tree and stand development. All commercial conifer species and the dominant broadleaved species, paper birch (*Betula papyrifera*), found in the region are considered. The overall objectives of this study are:

- 1. To develop predictive models for the number of years to reach breast height (YTBH) for both top-height (THT) and average-height (AHT) trees;
- 2. To develop predictive models for juvenile height yield above breast height (1.3 m) for both top-height and average-height trees; and,
- 3. To use site and stand attributes as predictors to explain variability in observed height.

These objectives were pursued through analysis of data collected in a related, Forest Renewal British Columbia (FRBC) funded growth and yield research project. This project involved the collection of height and age data from a range of young (13- to 32- year-old), managed, mixed-species stands, in the ICH BEC zone in the Neslon Region (Froese and Marshall 1998).

Three specific hypotheses were tested. Each was tested against the null hypothesis of no effect:

- 1. A biologically-reasonable model of YTBH as a function of site or stand variables explains a statistically-significant portion of the observed variability;
- 2. A biologically-reasonable height yield model as a function of site or stand variables explains a statistically-significant portion of the variability; and,
- 3. Separate models may be developed for YTBH and height yield for the "top height" and "average height" of the stand.

## 2. LITERATURE REVIEW

## 2.1 BACKGROUND

Many factors contribute, and interact, to define the height growth potential of, and height yield achieved for, individual trees (Oliver and Larson 1996). Site quality may be seen as the relative supply or availability, at a given location, of resources used by trees to achieve their genetic height (or some other attribute) potential. Genetics define the general adaptive approach for a species, including its height growth potential. Genetic potential also commonly varies with geographic location, in response to unique ecological conditions. The pattern of establishment and growth of a tree and its competitive relationships with neighbours, over time and in response to disturbance (stand dynamics), may limit or enhance the amount of potential achieved by an individual tree. Silvicultural treatments may also be applied that either directly affect tree growth (e.g., pruning), or indirectly affect growth potential (*e.g.*, fertilization).

## 2.2 SITE QUALITY

The quality of a site is assessed relative to a value of interest. For example, sites of high quality for one value or resource may or may not be of high quality for another. In forestry, systems of site quality classification have served two general purposes: to identify productivity and to provide a frame of reference for decisions regarding silvicultural prescriptions (Jones 1969; Carmean 1986). As forest management evolves to consider new values and smaller scales, such as biological diversity and wood technical quality, systems of classification will need to evolve (Smith 1980). In forestry, most interest in identifying site quality has been with respect to the production of timber. In this regard, there has been much argument about the best way to quantify quality objectively.

Early debate was between proponents of volume (Bates 1918; Roth 1918) and height (Watson 1917; Frothingham 1918; Chapman 1921). The most logical index of site quality with respect to a particular value is the measured yield of that value at a point in time of interest (Davis and Johnson 1987; Pfister 1988). The use of volume as an index of site quality is attractive in that it integrates the large numbers of variables that may affect the development of a stand. In this way, volume is the "final criterion", as suggested by Bates (1918) and Frothingham (1918, 1921).

However, when the integrated variables are subject to manipulation and when evaluating manipulations, such an index may not be meaningful. Cool (1965) suggested that a site quality index should be specifically *not* related to the components of yield which may be subject to change and manipulation and stated "... all other factors being equal, the [site quality index] will decide the difference in volume due to site." As early as 1918, the independence of the height of dominant trees from density and other factors, and the strong correlation between height and volume, had been recognized (Frothingham 1918, 1921; Roth 1918).

The general acceptance of the height of dominant trees, free from past suppression and damage and outside of density extremes, as independent of other stand factors (so-called 'top' or 'site'

height), continues to the present (Monserud 1984; Oliver and Larson 1996; Froese and Marshall 1997). This height is standardized into an index of site quality by reference of height to a particular tree age. This is 'site index' (Carmean 1975). While there are practical situations where top height, and thus site index, is impossible to assess (such as uneven-aged stands), it has gained wide acceptance as the preferred index for site quality, with respect to tree growth, in forestry (Carmean 1975; Tesch 1981).

When predicting the influence of site quality on tree height, it is intuitive to use height, and site index itself, as predictor variables. However, site index is rarely measured, because this would mean measuring height precisely at the index age. Therefore, site index is usually inferred. In general, inference is made using relationships between the index and other factors believed related to the index. Most commonly, these are so-called site index equations, where observed height at ages other than the index age is used to predict height at the index age.

This prediction may be made other ways, by measuring other variables that are believed to affect growth. Examples are relationships between site index and (after Froese and Marshall 1996):

- 1. other tree parameters, like basal area increment and height : diameter ratio (*e.g.*, Huang and Titus 1993; Site Productivity Working Group 1999);
- 2. soil physical and chemical properties (Carmean 1975; Kayahara 1989);
- 3. biogeographic descriptors (elevation, slope, aspect, latitude, longitude, 'habitat type' Wykoff *et al.* 1982); and,
- 4. derived units of other classification systems (ecosystem, vegetation or soil taxonomies Cajander 1926; Kayahara 1989).

When considering the influence of site on height yield, any one of these four approaches, along with site index, may be significant.

## 2.3 GENETICS

Perhaps the most basic factor affecting height development of trees is the genetic differences that define individual species. Different tree species have characteristic patterns of height development when grown under common conditions (*e.g.*, Omule and Krumlik 1987; Reukema and Smith 1987; Cobb 1988; Seidel 1989; Cameron 1996). This is almost universally recognized and forms the basis for many species selection guidelines for reforestation (Green and Klinka 1994).

Genetic variability within a species may be observed, and classified in different ways. Inherent growth patterns may be observed between families, or provenances, defined by geographic location (*e.g.*, Ying 1991; Xie and Ying 1995). Individual, or 'plus' trees with apparently superior attributes may be found within provenances. These differences have been the subject of much study because of the potential to exploit desirable trends. This may be achieved in two ways.

First, by identifying the most beneficial provenances or plus trees, for use in seed collection or tree seed orchards, plantations derived from this seed may have a greater occurrence of desirable attributes. Secondly, controlled breeding of these provenances and superior trees may be undertaken, with the goal of concentrating and identifying those individuals and families with the most desirable attributes. However, because potential gains may be balanced by potential losses, early results of studies into genetic variability are commonly guidelines for seed transfer in reforestation (*e.g.*, Matyas and Yeatman 1992; Xie and Ying 1993).

Despite efforts to take advantage of genetic variability, quantifying potential gain from tree breeding or provenance selection is difficult. Interactions between genotype and environment are common. Response surfaces for the many variables that describe inherent growth patterns between populations (termed the 'adaptive landscape' for a species) are inherently complex (Xie and Ying 1995). Most importantly, expected future gains are often predicted from early observations, so that results from breeding trials may be incorporated into the next breeding cycle. As such, expectations should be treated with caution. Examples of expected gain from tree breeding in the literature are shown in Table 1. Most note that the predicted gains are expected for one breeding cycle; additional gains could be achieved with subsequent cycles.

Species	Expected gain in height	Reference
black spruce (Picea mariana)	4.6 to 6.1%	Nelson and Mohn (1991)
Douglas-fir (coastal) (Pseudotsuga menziesii var. menziesii)	2 to 5%	Magnussen and Yanchuck (1994)
Jack pine ( <i>Pinus banksiana</i> )	5.1%	Rudolph <i>et al.</i> (1989)
interior lodgepole pine ( <i>Pinus contorta</i> var. <i>latifolia</i> )	2-6%	Ericsson (1994)
ponderosa pine ( <i>Pinus ponderosa</i> )	1 to 15%	Hamilton and Rehfeldt (1994)
western white pine ( <i>Pinus monticola</i> )	7%	Rehfeldt <i>et al.</i> (1991)
white spruce ( <i>Picea glauca</i> )	8%	Li <i>et al.</i> (1993)
white spruce	6 to 12%	Magnussen (1993)

Table 1. Potential increases in height growth associated with tree breeding.

There are few reports in the literature that attempt to quantify the effect of different provenances on height yield. Xie and Ying (1995) compared the height yield of six coastal lodgepole pine provenances at a single site on southern Vancouver Island. After 20 growing years, the average height of the shortest provenance was only 77% of that of the tallest. An information pamphlet

published under the Forest Resource Development Agreement (FRDA II)<sup>4</sup> suggested that increases in height for Sitka spruce (*Picea sitchensis*) and Douglas-fir may be obtained in coastal British Columbia using provenances from Washington State. Washington spruce provenances have outperformed local trees by 40% in total height in 10 years, while Douglas-fir provenances achieved gains of 10%, on average.

Although relatively few reports on actual gains from provenance selection or tree breeding may be found, many experiments have been performed in an attempt to reveal the adaptive landscape of various species (Xie and Ying 1995). Several different factors appear related to patterns of genetic variation. These include qualitative measures like geographic region and ecosystem type, and quantitative ones like elevation, latitude, longitude, frost-free period, and seasonal water deficit. Quantifying genetic variation within a species requires a multidimensional model.

Xie and Ying (1995) and Ying (1991) provide very comprehensive reviews of the adaptive landscape for lodgepole pine. These authors found a strong northwest/southeast trend in genetic variability in the species through its natural range in Canada. However, provenance altitude had a strong modifier effect, except at higher latitudes. Winter hardiness and tolerance of snow damage had a negative correlation with growth potential. Ying and Liang (1994) and Rehfeldt (1985) provide additional information on the adaptive landscape of lodgepole pine. Studies of adaptive landscapes may also be found for black spruce (Sulzer *et al.* 1993; Parker and van Niejenhuis 1994; Parker *et al.* 1996), Douglas-fir (Monserud and Rehfeldt 1990; Zhang *et al.* 1993), grand fir (*Abies grandis*) (Xie and Ying 1993), Jack pine (Magnussen and Yeatman 1988, 1989; Matyas and Yeatman 1992), ponderosa pine (Rehfeldt 1992a; Schaefer and Baer 1992), tamarack (*Larix laricina*) (Farmer *et al.* 1993), western larch (*Larix occidentalis*) (Rehfeldt 1992b; Zhang *et al.* 1994), and western white pine (Rehfeldt *et al.* 1991).

## 2.4 BETWEEN TREE COMPETITION

## 2.4.1 Pure Species Stands

It is widely accepted that dominant height yield is independent of density, for pure species, evenaged conifer stands, except at extremes (*e.g.*, Clutter *et al.* 1983; Smith 1986; Davis and Johnson 1987; Daniel *et al.* 1988; Oliver and Larson 1996). In contrast, average height is usually affected by density, as competition at some point in stand development induces differentiation into classes (Oliver and Larson 1996). Carmean (1975) cited studies by Ware and Stahein (1948), Ralston (1953), and Byrnes and Bramble (1955) as examples where the independence of dominant height yield across a range of densities was observed. Oliver and Larson (1996) cited Eversole (1955), Oliver (1967), Reukema (1970, 1979), Mitchell (1975), Lloyd and Jones (1983), and Hann and Ritchie (1988) in support of this concept. The idea that dominant height is independent of density

<sup>4</sup> Tree Improvement in B.C. A five-page brochure outlining the importance, process, and participation of various agencies in tree improvement programmes in British Columbia. Published under the Canada-B.C. Forest Resource Development Agreement (FRDA II).

forms the basis for the site index system, the most widespread index of site quality in use in North America (Carmean 1975, Tesch 1981).

Reukema and Smith (1987) provide a local example of dominant height/density relationships. In their study, three conifer species, Douglas-fir, western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*), were established in 1957/58 at the Malcolm Knapp Research Forest at Haney, B.C. Five different espacements were used: 0.91, 1.82, 2.74, 3.66, and 4.57 m (3, 6, 9, 12 and 15 feet). In the most recent remeasurement discussed by the authors, no significant difference ( $\alpha$ =0.05) in dominant height between any two spacings for any of the three species could be detected.

However, exceptions to the independence of density and dominant height are also present in the literature. For example, Xie and Ying (1995) reviewed the results of a lodgepole pine spacing/provenance trial in coastal British Columbia. In this experiment, six provenances, representing three locations along a northern and a southern east/west transect were established at seven spacings in a modified Nelder design. After 20 years, not only was height yield significantly different between provenances, but height increased with increasing density.

Another notable exception is the Douglas-fir spacing trial established at Wind River, USA (Eversole 1955; Reukema 1959; Curtis and Reukema 1970). In this trial, Douglas-fir was established in 1929 at six different square spacings; 1.22, 1.52, 1.82, 2.44, 3.05, and 3.66 m (4, 5, 6, 8, 10, and 12 feet). The re-measurement in 1965 indicated a statistically significant difference ( $\alpha$ =0.01) in height yield between the spacings (Curtis and Reukema 1970). Surprisingly, increased height yield was observed with decreased density, an opposite response to that reported by Xie and Ying (1995). The authors conclude by suggesting that substantial gains in productivity may be expected in Douglas-fir stands by controlling in favour of low density.

At high densities in some species under some conditions, the height yield of even dominant trees can be greatly curtailed. This process (repression) is most widely known in lodgepole pine (*e.g.*, Mitchell and Goudie 1980; Cieszewski and Bella 1993), but has also been observed in Douglas-fir (Reukema 1970, 1979) and ponderosa pine (Oliver 1967). Some of the reported effects of stand density on dominant height yield are presented in Table 2. The listed results should be interpreted with some caution, as it is not always clear from the publication whether average or dominant height was considered.

## 2.4.2 Mixed Species Stands

At very young ages, mixtures of species may not influence the growth of individual trees because trees have not grown large enough to compete with each other. However, different tree species have different patterns of height growth on a given site (Carmean 1970, Herman and Franklin 1976). These influence crown development and the competitive ability of individual trees (Oliver and Larson 1996). As a stand ages and individual trees interact, differences in height growth may accumulate and be expressed in stratification by species or differential competition-induced mortality (Young 1941; Wilson 1953; Grisez 1968; Kelty 1986; Clatterbuck and Hodges 1988;

Smith 1986; Simard 1990a; Oliver and Larson 1996). Stratification and dominance patterns may also change over time. For example, some tree species have slow but steady height growth even when relegated to lower canopy strata, which may allow them to eventually grow into upper crown layers (Oliver 1978; Larson 1986). Larson (1986) speculated that the greater resistance of grand fir to canopy abrasion is a significant factor in allowing the species to grow from lower crown classes into eventual dominance over Douglas-fir. Oliver and Larson (1996) suggest that overtopped strata may influence height growth in the overstory through competition for soil moisture, where moisture is limiting, even though they can not compete for light.

Species	Effect of Decreased Density on Height		Type of S	Source	
	Increased	Decreased	No effect	Manipulation	
black spruce				espacement	McClain <i>et al.</i> (1994)
Douglas-fir	, <b>v</b>		$\checkmark$	espacement, PCT, CT	Scanlin <i>et al.</i> (1981); Harrington and Reukema (1983); Omule (1987, 1988a); Reukema and Smith (1987); Meade and Leon (1992)
Engelmann spruce ( <i>Picea engelmannii)</i>			$\checkmark$	РСТ	Siedel (1984)
grand fir			$\checkmark$	РСТ	Scanlin <i>et al.</i> (1981)
jack pine			$\checkmark$	РСТ	Winston (1977); Smith (1983); Morris <i>et al.</i> (1994)
Jeffrey pine ( <i>Pinus jeffreyi</i> )	$\checkmark$			РСТ	Lilieholm <i>et al.</i> (1989)
lodgepole pine	$\checkmark$		$\checkmark$	espacement, PCT	Johnstone (1981, 1982); Siedel (1989); Xie and Ying (1995)
Norway spruce ( <i>Picea abies</i> )	$\checkmark$			espacement	Nilsson (1994)
ponderosa pine	$\checkmark$		$\checkmark$	espacement, PCT	Lilieholm <i>et al</i> . (1989); Siedel (1989); Cochran and Barrett (1993)
red pine ( <i>Pinus resinosa</i> )			$\checkmark$	espacement	McClain <i>et al.</i> (1994)
Sitka spruce			$\checkmark$	espacement, PCT	Pollack <i>et al.</i> 1990; Nelson (1991)
western hemlock			$\checkmark$	РСТ, СТ	Reukema and Smith (1987); Omule (1988b)
western larch			$\checkmark$	РСТ, СТ	Siedel (1975, 1984)
western redcedar			$\checkmark$	PCT	Reukema and Smith (1987); Harrington and Wierman (1990)
white spruce		$\checkmark$	$\checkmark$	espacement, PCT	Siedel (1984); Pollack <i>et al.</i> (1992); McClain <i>et al.</i> (1994)

Table 2. Studies that have examined the impacts of stand density on height.

Note: PCT is pre-commercial thinning; CT is commercial thinning.

Most reviews of mixed-species stand development have focused on revealing characteristic developmental patterns of common species groupings. For example, Murray and Leonard (1990) concluded that mixtures of western hemlock and pacific silver fir (*Abies amabalis*) have similar growth patterns over a common rotation. However, they differ in growth through developmental stages of that rotation. Cobb *et al.* (1992) and O'Hara (1993) reviewed stand structure and

stratification patterns in various stand types in the Wentachee National Forest in the eastern Washington Cascades. The authors used stand reconstruction techniques to reveal height growth patterns in stands of apparently different climax vegetation potential. In both studies, the authors concluded that reasonably consistent developmental patterns and differentiation by species occurred over a wide range of stand and site conditions. Oliver and Larson (1996) outlined several additional examples of differentiation by species in western coniferous mixtures. Where Douglas-fir, grand-fir and western larch grow in mixtures in the northern US Rocky Mountains, western larch either becomes emergent over a canopy of the other two species or dominates the canopy where more numerous (Mosher 1965; Cobb 1988). Where lodgepole pine is present in the mixtures, it outgrows western larch for the first few decades until eventually overtopped by the larch, after which the pine declines in number. When larch and pine are infrequent and do not compete with each other, their development patterns are unaltered. Where Douglas-fir and grand fir grow in mixtures of Sitka spruce and western hemlock in southeastern Alaska have developed similarly in height, but hemlock suffers higher mortality (Deal *et al.* 1989).

It is apparent that average height is partly dependent on the dynamic relationship between trees in most mixed-species stands. This relationship is often strongly influenced by site quality, with one species outgrowing another on rich sites, and the reverse on poorer sites (Doolittle 1958; Wierman and Oliver 1979; Oliver and Larson 1996). Therefore, it is important to consider site quality and the specific species mixture and proportion, as well as the interaction between them, when forecasting stand dynamics in mixed species stands.

However, where the growth habits of different species are similar enough, it may be possible to forecast their dynamics as if the stand was composed of a single species (Mitchell *et al.* 1995). For example, in the western Cascades mixtures of western hemlock and pacific silver fir have similar height growth patterns (Herman 1967). Oliver and Larson (1996) suggested that they may be similar enough in development to behave much like single-species stands. Alternately, where species mixtures are "coarse", with different species essentially aggregated into groups, the effect of developmental differences at the stand level may be minor (Mitchell *et al.* 1995).

## 2.5 SILVICULTURE

#### 2.5.1 Thinning

Common silviculture treatments applied in British Columbia involve manipulating stand density (*e.g.*, espacement, pre-commercial or commercial thinning). Thinning can have an immediate impact on the average height of a stand and perhaps on the dominant height of a stand, depending upon the type of thinning applied (the so-called 'chain saw effect'). Subsequent height growth may also be affected on some portion or all of the residual trees, which may be attributable to the residual density (see Section 2.4). Thinning may also affect long-term competitive interaction where species are removed in differing proportions.

#### 2.5.2 Site preparation

Literature on the effects of site preparation on height yield, damage, and survival of planted trees is abundant. Site preparation treatments include prescribed fire, mechanical manipulations of slash, duff and soil, and herbicide application. The reasons for using site preparation include improving access, creating planting spots or seedbeds for desired vegetation, improving the environment for growth, and controlling competing vegetation (Otchere-Boateng and Herring 1990; Haeussler 1991; Von der Gönna 1992; Farnden 1994). However, relatively little literature may be found on the influence of site preparation on growth after a stand is established and height exceeds breast height<sup>5</sup>. This is possibly because the influences of the ground level environment on tree height growth are dampened once trees achieve crown closure.

Many site preparation treatments, which report increases in height growth, credit the response to reducing competing vegetation. Prescott and Weetman (1994) reported increased early height growth in western hemlock and western redcedar on sites where prescribed burning or clipping reduced salal (*Gaultheria shallon*) cover. Fraser *et al.* (1995) reported similar increases in hemlock early height growth with reductions in salal cover following scarification and fertilization. They also reported increases in western redcedar height growth with site preparation, but the increases were apparently unrelated to reductions in salal cover. Vihnanek and Ballard (1988) reported increased height growth of Douglas-fir after slashburning on eastern Vancouver Island. Salal cover was reduced with burning; however, the authors did not explicitly design the study to demonstrate a correlation between salal reduction and improved height growth.

In a stumping trial designed to reduce the influence of root disease on Douglas-fir in coastal Washington, Thies and Nelson (1988) reported an increase in early height growth following complete stump removal. They noted that thorough stumping required almost complete coverage of the site by machines, which destroyed nearly all vegetation present. A similar study by Smith and Wass (1994) reported no effect on Douglas-fir height growth in undisturbed soil and areas of soil deposits, but reductions in growth were found where the soil was compacted by machinery. Soil compaction was not substantial in the trial by Thies and Nelson (1988), apparently because of coarse soil, and the dry conditions present at the time of treatment.

Some site preparation treatments are designed to improve early seedling growth by warming the soil or improving the moisture condition at the planting location (*e.g.*, Coates and Haeussler 1990, Stathers *et al.* 1990). These treatments may continue to influence height growth beyond breast height. For example, Fries (1993) reported increased dominant height growth both below and above 1.3 m for lodgepole and Scots pine (*Pinus sylvestris*) with patch scarification or mounding. Increases in height growth may also be long lasting where waterlogged sites are improved through drainage (*e.g.*, Williams *et al.* 1991; Meng and Seymour 1992).

<sup>&</sup>lt;sup>5</sup> In Canada, breast height is usually defined as 1.3 m above ground. In the United States, breast height is 1.4 m (4.5 feet) above ground. In this thesis, as long as the intended height may be determined from the context of the referece, the term 'breast height' is used without distinguishing the precise definition.

Certain site disturbances appear to influence growth over very long spans of time. One hypothesis of the SCHIRP (Salal Cedar Hemlock Integrated Research Program) project (Prescott and Weetman 1994) serves as a good example. Substantially greater growth was observed for second-growth stands of western redcedar and western hemlock established on sites previously occupied by hemlock and Pacific silver fir (HA sites) than on sites previously occupied by western hemlock and western redcedar (CH sites). It was hypothesized that the CH sites established after long periods without disturbance and accumulated thick layers of poorly decomposed, nutrient poor, redcedar wood and litter. In contrast, HA sites established after periodic windthrow, in which treefall resulted in soil mixing which improved aeration, decomposition and nutrient cycling. However, Stephens *et al.* (1969) hypothesized the opposite impact of windthrow. They found that stands of Sitka spruce in southeast Alaska that regenerated after windthrow were significantly shorter at a given age than stands that regenerated after wildfire or logging. They attributed this to the abundance of organic matter generated in a windthrow event and believed that this forms a thick, insulating blanket, which retards decomposition and nutrient cycling.

Other severe treatments appear to have long-lasting negative effects on height. Slashburning in Douglas-fir clearcuts in northern California resulted in 88% reductions in top-height yield (Heavilin 1977). Ball (1990) reported profound, long-lasting reductions in white spruce growth in British Columbia with heavy blade scarification. Wood and Dominy (1988) reported similar reductions in white spruce height growth.

## 2.5.3 Planting

Planting facilitates the establishment of preferred trees over natural regeneration. This may be desirable where natural regeneration of a desired species is slow or rare, or where natural regeneration of undesirable species is likely. Planting is necessary where the desired species is not naturally present, such as with exotic species or old fields. Most commonly, planting is used to:

- 1) establish trees on a given site with a greater growth potential than those currently present, or likely to establish naturally;
- 2) achieve regeneration faster than would occur through natural seed-in, thereby increasing tree height relative to time since disturbance, independent of growth rate;
- 3) establish trees which are one or more years old, with pre-developed root systems, which are buffered from site conditions and which can more rapidly acclimatize and exploit site resources; and
- 4) establish large trees, thereby getting a head-start over competing vegetation.

Numerous references on the effects of planting on tree growth exist. The vast majority of these refer to the rapid re-establishment of forest stands; few refer to the effects on tree growth beyond breast height. The height achieved at a given time since disturbance will be greater if height

growth is accelerated below breast height. However, if growth beyond breast height is not affected by planting, the height at a given breast-height age (BHA) may not differ.

The major impetus for planting is to favour desired trees over competing vegetation; Newton *et al.* (1993) provide an excellent example. In their study, small plug stock of Sitka spruce, Douglas-fir and western hemlock were spring-planted on two sites, freshly slashburned and underneath four-year-old salmonberry (*Rubus spectabilis*), on the central Oregon coast. In the fall, half of the salmonberry sites were treated with herbicide to release the trees from competition. In addition, three sizes of wildlings (30, 60 and 90 cm in height) for hemlock and Douglas-fir, and two sizes of large Douglas-fir bareroot stock were planted in each treatment. Height and diameter measurements were made 10-14 years after planting. In each case, the use of larger planting stock significantly increased final height over small plug stock. Release from salmonberry provided 6 and 9% increases in height and diameter, respectively, and a 20% increase in volume growth. Conclusions could not be drawn from Sitka spruce because of repeated leader damage by insects. It is not apparent whether the increased final height was the product of increased height growth above or below breast height (or both), because all growth measurements were reported relative to the time of establishment.

In a paired-plot trial using planted and naturally established Douglas-fir, Miller *et al.* (1993) examined growth with specific reference to BHA. The growth of 75 adjacent natural and planted stands, established after slashburning, were compared across seven sites in western Oregon. Measurements were made on the largest 40 trees per acre. BHA at time of measurement ranged from 24 to 29 years. The experimental design precluded drawing specific conclusions based on statistical analyses. Nevertheless, trends indicated that natural trees took 3.0 years longer to reach breast height. Despite poorer growth below breast-height, the difference in BHA was accompanied by only a 0.82 m (2.7 foot) difference in height, on average. This study supports the notion that planting may not change the potential for growth once trees are established and growing above competing vegetation, all other factors being equal, including the genetic height growth potential.

However, all factors are not usually equal when comparing planted and natural regeneration. The increased above-ground size of planting stock, which may convey an advantage in early growth, is usually paralleled by an increase in the below-ground size of the stock. This poses several problems. First, large bareroot stock is difficult to plant so that the root systems are naturally distributed. Also, the root systems of container stock are limited by the size of the container.

Reports of reduced stability in some young plantations, and suspicions raised by observing seedling roots, have resulted in several comparative studies of natural stands and plantations. Halter *et al.* (1993) and Halter and Chanway (1993) are two examples of such studies. In the former, 12-year-old natural and planted lodgepole pine were compared at a site near Terrace, British Columbia. The results indicated that natural trees had greater total height, more first-order lateral roots and more sinker roots than planted trees. The effects persisted beyond breast height, as leader growth in the last two years was greater in natural trees as well. Halter and Chanway (1993) conducted a similar study in Douglas-fir and lodgepole pine near Golden, B.C. At age 11,

natural trees were taller, had greater leader growth in the past two years, 2.3 times as many lateral roots, and more than twice as many lateral roots within the top 10 cm of the soil surface. In both cases, the authors noted that the effects of the container on root morphology were clearly evident at the time of measurement, and that the presence of root deformities was much greater in planted stock.

McDonald (1991) compared the difference between Douglas-fir and ponderosa pine bareroot and container planted stock types in California. For ponderosa pine at two of three sites, height growth beyond breast height was greater for container stock. Height growth of Douglas-fir container stock was greater at one of two sites as well. McDonald suggested that container stock produced better tap and sinker roots than bareroot stock, which was advantageous on the very dry study sites.

## 2.5.4 Brushing

Site treatments undertaken after a stand is established are usually "release" treatments. These treatments are designed to reduce or eliminate competition between crop trees and non-crop trees or other vegetation. Although there are a large number of references in the literature discussing the use of herbicides and mechanical approaches for reducing non-crop vegetation, the vast majority of these studies consider only site preparation (pre-establishment) treatments. Nevertheless, the effects of competing species on the growth of conifers beyond establishment and breast height are well documented. This is especially true in the case of overtopping and suppression of confers by competing species with rapid juvenile height growth (*e.g.*, Allan *et al.* 1978; Howard and Newton 1984; Cole and Newton 1987; Simard 1990a,b).

Preest (1977) reported on a trial using eight combinations of herbicidal weed control on Douglasfir plantations in coastal Oregon. Single applications of herbicide resulted in increased height yield over controls; however, repeated applications (over several years) resulted in greater, additive increases. Wood and Dominy (1988) examined the effect of herbicide application on white spruce planted under two different pre-establishment mechanical site-preparation treatments. Herbicide application improved spruce height yield only on one site preparation treatment, apparently because the other was so severe as to dramatically reduce site fertility and both crop and non-crop species growth. Allan *et al.* (1978) and Harrington *et al.* (1995) also reported increases in Douglas-fir height yield using herbicides for release. The latter reported increases in height yield only with repeated application of glyphosate, and reductions relative to controls with application of triclopyr, indicating herbicide injury to crop trees.

Increases in height yield were also reported with physical removal of competing vegetation. Sharrow *et al.* (1992) reported a 6% increase in Douglas-fir height at age 10 over controls, following browsing of competing vegetation by sheep. The response was limited because sheep occasionally browsed on the Douglas-fir as well. In a 20-year-old spacing trial using ponderosa pine, those stands without control of shrubs achieved only 80% of the height yield of stands with control (Oliver 1990). In this trial, vegetation control was initially through herbicides, but after four years was achieved through hand removal. McDonald *et al.* (1994) found increased ponderosa pine height yield with physical control of non-crop woody and herbaceous vegetation. Physical removal of salal from 10 to 16-year-old plantations of western hemlock, western redcedar and Sitka spruce resulted in increased height growth in all three species (Prescott and Weetman 1994).

Some reports on physical removal of vegetation do not demonstrate an increase in crop tree height. Harrington *et al.* (1995) included a physical removal treatment in their study of the response of Douglas-fir to various approaches, and this treatment had no significant effect on height at age 10.

## 2.5.5 Fertilization

Fertilization studies are common in the literature. Some examples of fertilization research on local species that demonstrate increased height with fertilization are given in Table 3. Douglas-fir appears to have had the most fertilization research of all the B.C. tree species.

Virtually all references regarding tree response to fertilization show increases in growth of tree attributes, including height. The almost universal increases in growth found with fertilization demonstrate that most plants do not grow in environments without some nutrient limitations. Nitrogen is widely recognized as the most common nutrient limiting growth in temperate and boreal forests (Smith 1986; Oliver and Larson 1996).

Species	Authors
Douglas-fir	Scanlin <i>et al.</i> (1981); Thies and Nelson (1988); Green and Carter (1993); Henry <i>et al.</i> (1993); Thies <i>et al.</i> (1994)
grand fir	Scanlin <i>et al.</i> (1981)
Sitka spruce	Harris <i>et al.</i> (1981)
western hemlock	Fraser <i>et al.</i> (1995)
western redcedar	Harrington and Wierman (1990); Fraser <i>et al</i> . (1995)

Table 3. Fertilization studies that have examined the effect on height.

Most trials have involved inorganic fertilizers, but responses to organic forms have also been demonstrated (*e.g.*, Henry *et al.* 1993; McDonald *et al.* 1994; Fraser *et al.* 1995). Nitrogen is often noted as most commonly deficient nutrient in temperate forests (Gessel *et al.* 1979; Vihnanek and Ballard 1988) consequently, it is the most commonly applied nutrient. Nitrogen is also often cited as being the most limiting nutrient in fertilizer trials when combinations are tested (*e.g.*, Brockley 1992). Nevertheless, other nutrients may limit height growth, such as boron in coastal Douglas-fir (Green and Carter 1993).

The relationship between application rate and height-growth response varies. Intuitively, a greater response would be expected to increasing additions of fertilizer as long as nutrient demand exceeds supply. On rich sites, maximum response may be achieved with lower additions (*e.g.*, Winston 1977). Fertilization may not increase growth on deficient sites if another necessary factor for growth is limiting, such as water or the length of the growing season. A greater response for a

given addition of fertilizer is likely on sites where other resources are not in short supply. For example, Henry *et al.* (1993) observed greater response to fertilization on sites rated as more productive before fertilization was undertaken.

### 2.5.6 Pruning

The potential of pruning to improve wood quality has long been recognized. Many references may be found in the literature regarding the effect of pruning on wood quality and tree form, for a variety of native and exotic species in North America (*e.g.*, O'Hara 1991; O'Hara *et al.* 1995). Much of the focus has been on identifying the potential responses to pruning, and in developing financially and biologically optimum pruning regimes.

To be effective, pruning must be done when trees are young. This ensures that small knots and a small knotty tree core are rapidly eclipsed by clearwood. Therefore, pruning is most cost-effectively achieved on high-productivity sites. As a result, most of the pruning-related literature is focused on the fast-growing pine forests in the southeastern U.S. and New Zealand, and on the forests of the Pacific Northwest. The pool of literature on the impact of pruning on northern temperate and boreal species is dominated by studies on Douglas-fir.

The most common response to pruning reported is a reduction in volume growth (*e.g.*, Stein 1955; Slabaugh 1957; Moller 1960; Staebler 1963, 1964; Langstrom and Hellqvist 1991). This reduction may occur with mild (light) or severe pruning; however, mild pruning (pruning up to 30% of the live crown) does not appear to affect height growth (Stein 1955; Slabaugh 1957; Moller 1960; Staebler 1963, 1964). Thus, the reduced volume growth following pruning appears to be predominantly the result of reduced diameter growth. Specific results are presented in Table 4.

		Ū	
Species	Effect of Pruning on Height Growth	Amount of Pruning Associated with the Effect	Reference
Douglas-fir	reduction	removing 2/3 of the live crown	Staebler (1963, 1964)
	reduction	more than 1/2 of the live crown	Stein (1955)
	reduction	to less than 50% live crown ratio	O' Hara (1991)
	none	less than 1/2 of the live crown	Staebler (1963, 1964)
	none	1/4 to 1/3 of the live crown	Stein (1955)
	increase	1/4 of the live crown	Stein (1955)
Scots pine	none	up to 75% needle biomass	Langstrom and Hellqvist (1991)
red pine	reduction	more than 1/2 of the live crown	Slabaugh (1957)
	none	less than 1/2 of the live crown	Slabaugh (1957)

Table 4. Impacts of pruning on tree height.

### 2.6 JUVENILE HEIGHT MODELLING

### 2.6.1 Simple Approximations

The simplest approach for providing information on juvenile height yield is to develop simple averages based on formal or informal observation. This method was used in the most recent (1991-1996) timber supply analysis in the Kootenay Lake Timber Supply Area (TSA) (Ministry of Forests 1993). In the timber supply analysis, the management of a number of non-timber resources involves constraining forest disturbance so that a minimum amount of certain forest structures are maintained at all times (Table 5).

These requirements specified for a planning unit:

- the maximum amount of forest area that may be in a harvested or immature state;
- the height regenerated stands must achieve before adjacent areas may be harvested ("greenup" height); and,
- the minimum amounts of special forest cover (old growth or wildlife habitat) that must be present.

Management Zone	Proportion of timber land base (percent)	Max. immature area (percent)	Green-up age (years)	Min. area in special cover (percent)	Min. age of special cover (percent)
Deer / elk winter range	1.3	33	20	40	46
Caribou late winter range	10.6	33	20	50	120
Low elevation moose / caribou winter range	3.0	33	20	60	46
High elevation moose / caribou winter range	1.5	33	20	30	46
Visual Quality Objective 'M'	4.0	25	30	10	140
Visual Quality Objective 'PR'	18.4	16	30	10	140
Visual Quality Objective 'R'	4.3	5	30	10	140
Licensed special watersheds	18.3	25	31	10	140
Licensed watersheds	3.9	30	31	10	140
Unlicensed special watersheds	22.5	33	31	10	140
Special watersheds	10.6	33	20	10	140

Table 5. Kootenay Lake TSA management zones and forest cover requirements.

Source: B.C. Ministry of Forests, Kootenay Lake Timber Supply Area Timber Supply Review Discussion Paper, July 1994. Notes: Visual quality objectives stated are classes of permitted disturbance; "M" is modification, "PR" is partial retention and "R" is retention. "Licensed" watersheds provide water to holders of water licenses for domestic and other uses. "Special" watersheds have additional considerations, such as critical fish spawning areas or high levels of licensed use.

The values under management by these constraints – wildlife habitat, visual quality, and water resources – depend on tree and stand height. Management planning, however, depends on the timing associated with critical heights; hence only ages are commonly reported (Table 5). The age

at which a stand achieved a critical height was estimated, for the timber supply analysis, using silviculture survey records and professional experience. Green-up height was determined to be seven metres, and an estimate of 31 years was necessary to achieve this height (Ministry of Forests 1993). Similarly, an estimate of 46 years was made for achievement of wildlife habitat requirements of 20 m in height. The strength of this approach to estimating height yield is that it is based on local data and is readily obtained.

However, this approach has many obvious weaknesses. For example, although based partially on survey data, the estimate is undoubtedly biased. Several attributes of the Kootenay Lake TSA suggest that this bias may be large. Harvesting has been concentrated in the relatively productive, mid-elevation regions that escaped wildfires during the late 1800s and early 1900s. While this area is arguably the most productive in the TSA, severe brush competition and failure of planted and natural regeneration in stands harvested before 1984 is common (more than 50% of stands visited in pilot sampling were classified as "not sufficiently restocked"). More importantly, where the objective is spatially explicit management of non-timber resources at the watershed scale, the precision of a regional average is likely inadequate.

## 2.6.2 Site Index and Height Models

More precise models of height yield than simple approximations do exist at for mixed-species stands in the Nelson Region. The most common models are consequential to the emergence of site index (SI) as the dominant system of site quality estimation in North America (Carmean 1975; Tesch 1981). Under the SI system, the attained height of a tree of a given species at a reference age is used as an expression of site quality. To ensure height is affected by site quality alone, selection of trees focuses on individuals which are free of any evidence of competition or stem damage (top-height trees).

However, because SI may only be measured at index age, it is more commonly predicted for a given tree using models developed from stem analysis data. These models relate height and age measurements to the attained height at a reference age (usually 50 years BHA). Data used to develop these relationships may also be used to model the height development of a tree as a function of age and site. Commonly, these relationships describe height as a function of BHA, species, and an index of site quality. This is because the influence of shrubby and herbaceous competing vegetation on growth above this height is often minor. However, height yield below breast height may be very important, where stand condition with respect to age of disturbance is important, such as actual rotation length since disturbance. Treatments or factors that influence this part of tree development may be of interest under these circumstances.

Several problems exist with existing height yield models. Most height yield and site index curves developed in western North America use stem analysis from trees in uncut, naturally established stands. As a result, sample trees often range in age from 60 to 200 years, and in some cases to nearly 400 years of age (*e.g.*, Stage 1963; Monserud 1984; Thrower and Goudie 1992). The assumption that tree height development is unaffected by damaging agents and changes in climate grows more tenuous as stand age increases. In their study, Murray *et al.* (1991) concluded that

juvenile height yield of Pacific silver fir and noble fir (*Abies procera*) was substantially underestimated by models developed from older stands. Although they acknowledge that their sample data were predominantly from better sites, the authors conclude that the magnitude of difference is not wholly explained by site. The authors suggested that difference in vegetative competition between logged and naturally disturbed sites, climate change, or shifts in competitive status are possible explanations for the observed differences.

Height yield and SI models have also been found to be imprecise at young ages. Nigh and Sit (1996) examined error in height and SI predictions from white spruce SI and height yield models. Errors in predicted height were as high as 2 m at 20 years BHA, with a 95% confidence interval for mean height of  $\pm$  0.75 m. Growth intercept (GI) models developed recently were designed in part to address this deficiency; although an improvement over traditional SI models they still contain appreciable error (*e.g.*, Nigh 2000).

### 2.6.3 Juvenile Height Models

Models of height developed explicitly for juvenile trees are rare in the literature. Nigh and Love (1999) developed a model for estimating juvenile height of lodgepole pine in the Prince Rupert Forest Region of B.C. Data to fit the model were collected from 46 juvenile stands less than 20 years old in which only top-height trees were sampled from each 0.04 ha plot. Only areas free from suppression from competing vegetation were eligible. The data collection method was precise and intensive; each tree was split longitudinally using wedges and past height development reconstructed by locating scars left by terminal buds. Site index was used as a predictor in addition to age, although it was predicted from the same trees used to develop the height model. The authors accepted the estimation error that came from this method. The model developed was a Type I Combined Exponental and Power Function (Sit and Poulin-Costello 1994):

$$HT' = (a + b \cdot SI) \cdot AGE^{c} \cdot d^{(AGE)},$$

where HT' is predicted total height above ground at a given AGE, SI is site index estimated using a GI equation (Nigh 1997) in metres (m) and *a* through *d* are estimated coefficients. The model was fit as a both as a height yield model and as height growth model, with an explicit error structure to remove serial correlation from the data. The authors did not present coefficient of determination ( $R^2$ ) and root mean square error (RMSE) values for the models. Rather, they compared the mean and variance of prediction errors (residuals) between the two models, concluding that analyzing growth instead of height yield did not reduce model performance.

Omule and Krumlik (1987) developed juvenile height models for Douglas-fir, western redcedar, western hemlock and Sitka spruce using data collected from an espacement trial installed at three sites in coastal B.C.. All trees were planted in 1962 and 1963 and re-measured periodically through 1985. A separate model was developed for each species and site unit; site units were four classes defined by soil moisture and nutrient regime.

The function used for each model was the Power Function (Sit and Poulin-Costello 1994):

$$HT' = a \cdot AGE^{b}$$
,

where *a* and *b* are estimated coefficients. The estimated models had R<sup>2</sup> values from 0.526 to 0.980 and RMSE values from 0.089 to 0.446 m. The authors concluded that detectable differences exist between species and sites; however, the developed curves conform to the general shape and magnitude of other published height yield curves for the region. Using the final fitted models, YTBH predictions ranged from lows of 2 years (Douglas-fir, western hemlock, Sitka spruce) to 6 to 10 years (Douglas-fir and western redcedar, respectively).

Preliminary height yield models for juvenile stands have been also developed for lodgepole pine and interior spruce (*Picea glauca X engelmannii*) in the Nelson Region. Thompson (1996) developed a model for lodgepole pine, in which data used for modelling came from a provenance study established in 1974 at 15 locations in across the region. All sites received silvicultural treatments to ensure height growth was not impeded. Elevation was the only variable (other than age) included in the height model as a predictor. The model developed was a Type II Combined Exponential and Power Function (Sit and Poulin-Costello 1994):

$$HT' = a \cdot AGE^{b} \cdot e^{(c \cdot AGE + d \cdot ELEVATION)},$$

where ELEVATION is in metres above sea level and *a* through *d* are estimated coefficients. The estimated model had an R<sup>2</sup> of 0.944 and RMSE of 0.687 m. Thompson notes that aspect, slope, soil moisture and soil nutrient status were not included in the model, although they were measured. He adds that "observation suggests that incorporation of these factors into the model should improve the relationships developed … but with only 13 sites … there was insufficient depth to attempt to include them in the model." Using the fitted model, YTBH was predicted as 4 to 6 years, and the number of years to reach a height of 7 m as 15 to 24 years, at 800 and 1600 m in elevation, respectively.

Thompson (1995) also developed a juvenile height yield model for interior spruce in the Nelson Region. Elevation was also used as a predictor in the spruce model; however, in contrast to the lodgepole pine model, the data collected were from operational stands that may or may not have received vegetation control. Furthermore, instead of fitting the model to height and age measurements for trees, the input data were average plantation heights and ages. To produce height trajectories, the heights and ages of preceding internodes were also measured, increasing the effective size of the data set. The model developed was a Type I Exponential Function (Sit and Poulin-Costello 1994):

$$HT' = e^{(a+b\cdot AGE + c\cdot ELEVATION^2)},$$

where *a* through *c* are estimated coefficients. A separate model was developed for three elevation classes (800, 1200 and 1600 m). The estimated models had  $R^2$  values from 0.702 to 0.860 and RMSE values from 0.180 to 0.283 m. Thompson noted that incorporation of aspect and slope

should improve the relationships developed. Using the final fitted models, YTBH is predicted as 8 to 11 years. Because the model fitting data were available only to 3.5 m, the number of years to reach 7 m was not estimated.

#### 2.6.4 Incorporating Site

Some measure of site quality is incorporated into most height yield models. Interestingly, many site index models are actually fit as height models, then inverted to solve for SI. Two methods presented by Clutter *et al.* (1983) for constructing height models (to be used as SI models), are the "guide curve" method and the "parameter prediction" method. In the guide curve method, a single height yield model is fit to height and age data, producing an "average" line for the sample data used (Clutter *et al.* 1983). Scaling the guide curve produces curves for different SI values. In the parameter prediction method, the height yield model being used (the base model) is fit to each sample tree or plot, and the parameters of the model are themselves modeled as functions of site. This method requires re-measured plots or multiple measurements per sample tree to produce the trajectories for fitting. Alternatively, the coefficients of the base model may be replaced with functions of SI, and the entire model estimated simultaneously.

For many mathematical functions that are useful base models of height yield, different parameters define different attributes of the curves that may be produced. For example, in the Power function the parameter *a* defines the rate of change, and the parameter *b* the shape (Sit and Poulin-Costello 1994). For the Type I Combined Exponential and Power function, no parameter controls a single attribute, but for values of *b* and *c* greater than one, the roles are similar to the Power function. These parameters may be hypothesized as functions of independent variables. However, it can be difficult to determine *a priori* which independent variables to include and which combinations to explore.

In the guide curve method, differences in trajectory due to site are assumed to be expressed in rate of change and not in shape. These are anamorphic curves (Clutter *et al.* 1983), and under this assumption site attributes are used only to model the *a* parameter. The lodgepole pine model by Nigh (1999) is an example of an anamorphic family of curves. This is a reasonable approach in cases of a limited amount of data or where apparent trends suggest an anamorphic approach is biologically reasonable. In contrast, the parameter prediction method produces polymorphic curves, because both the scale and shape parameters of the base model are expressed as functions of site. This approach is feasible where the number of combinations of independent variables is small. Otherwise, a very large model with many coefficients may result, and generating appropriate seed values for non-linear estimation becomes complex.

# 3. METHODS

## 3.1 THE INTERIOR CEDAR-HEMLOCK BIOGEOCLIMATIC ZONE

Data for this thesis were collected from the ICH BEC zone. The zone is found in the low to middle elevations in southeastern B.C. in the narrow, deep valleys of the Columbia Mountains, and much of the Shuswap and Quesnel Highlands. The climate of the ICH is interior continental and is dominated by easterly moving air masses, producing cool, wet winters and warm, dry summers. Eleven ICH subzones have been designated; much of the area around Nelson falls into the ICHdw (dry, warm) and ICHmw2 (moist, warm, Columbia-Shuswap variant) subzones.

In the Nelson Region, the ICH is divided into dry, moist and wet climatic regions; the dw and mw2 subzones are part of the moist region (Braumandl and Curran 1992). The ICHdw is found in valley bottoms up to 1200 m in elevation. The mw2 is above the dw up to approximately 1450 m, depending on aspect. Both subzones have hot to very hot, moist summers and very mild winters with light snowfall (Table 6). However, soils stay moist well into summer due runoff from melting snowpack. The forests of the ICH are diverse and extensive. Grand fir forms a component of climax stands in the southernmost ranges, and white spruce, Engelmann spruce, and spruce hybrids with subalpine fir in the north, especially in areas of cold air drainage

	BEC Subzone			
Climatic Attribute	ICHdw	ICHmw2		
Mean Summer Temperature (°C)	>12.6	10.1-12.5		
Mean Summer precipitation (mm)	200-230	200-230		
Mean Winter Temperature (°C)	>1.5	>1.5		
Mean Snowfall (mm water equivalent)	200-350	200-350		
Mean Snowpack (cm)	<80	<150		

Table 6. Climatic Characteristics of the ICHdw and ICHmw2 subzones.

Note: Adapted from Braumandl and Curran (1992).

#### 3.2 SAMPLING DESIGN

In this research, two different populations were sampled for each tree species of interest. They were called the top-height and average-height populations (Table 7). The AHT population simply constituted all trees of a given species within a selected stand. The top-height population was a subset of trees, identified according to the following definition:

Within a 0.01 hectare plot, the largest diameter dominant or co-dominant tree of a species present on the plot, without any evidence of suppression or damage that has impaired height growth above breast height, evaluated by visual examination of the bole and of annual growth rings on an increment core taken at breast-height.

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	Top Height	Average Height
Population	All possible 0.01 ha subplots with a top-height tree	All trees
Sampling Unit	Subplot	One tree per species selected randomly on a subplot
Measurement	Attributes of the top-height tree within the subplot	Attributes of the sample tree
Sample design	One stage cluster with a maximum of four elements per cluster	Three stage with an unequal total of secondaries and tertiaries per primary

Table 7. Sampling attributes of the top and average-height populations.

Two types of trees received special consideration: veteran trees (mature trees that survived the most recent stand-replacing disturbance) and advance regeneration (immature trees that regenerated in advance of the most recent stand-replacing disturbance). Advance regeneration were not considered part of the top-height population; however, where found, they were included in the average-height population. All commercial conifer species found were sampled, as well as one species of hardwood.

The overall sampling design emphasis was on capturing the range of conditions found in the region, because the central goal of this research was the development of height prediction models. This is in contrast to sampling with strict randomization, where the goals are unbiased estimates of population parameters. Sampling across the range of conditions can be more efficient in developing regression models (Demaerschalk and Kozak 1974). The selected approach was to identify all stands within a short (1.5 hour) drive of Nelson, British Columbia that had experienced stand-replacing disturbance between 1965 and 1985. From the list of identified stands a number were selected and visited to confirm access and evaluate suitability. The original intent was to divide the list into classes by slope, aspect and elevation, from which sample stands would be selected randomly. However, access and suitability was unpredictable; selection was made by visiting all stands in a watershed until one that met the selection criteria above was found.

In each stand selected for sampling, a systematic grid of six sample points was established (Figure 1). The grid spacing was selected to ensure complete coverage of the stand, and the location of the first point was selected randomly. At each sample point, a 0.04 ha (11.25 m radius) circular plot was established, and divided into four sub-plots along cardinal bearings. Measurements of site attributes were made at the stand and plot level, and measurements were made on trees of both THT and AHT populations at the subplot level.

Two specific processes were implemented to improve efficiency. For the THT population, multiple non-destructive measurements were made on sample trees, where possible (Figure 2). This was achieved by successive measurement of height at points of cessation of height growth in years prior to the most recent complete growing season. Age at these points was determined by subtraction from total age. These measurements were only possible on trees that produce strong branches at the point of cessation of height growth ("terminal branches"), such as Douglas-fir.



Figure 1. Example of plot design and layout in a hypothetical stand.



Figure 2. Determination of past height.

Secondly, only one tree of each species in the AHT population in a sub-plot was measured. This tree was selected randomly from the pool of trees of that species present. While this reduced the number of measurements, all trees in a plot had to be identified (enumerated) so random selection could be made.

## 3.3 SAMPLING PROCEDURES

Field sampling was completed in the summers of 1996 and 1997. All tree measurements were made in 1996; sampling in 1997 was confined to plot measurements of vegetation and soil attributes. In the remainder of this thesis, both seasons are treated as if they were one. Because random selection of AHT trees required complete enumeration before selection could be made, sampling was completed in two phases. Plots were located and trees identified in the first phase, and sub-sample trees selected and measured in the second phase.

#### 3.3.1 Phase 1

For each selected stand, the access procedure, forest cover mapsheet, forest cover polygon number and silviculture opening number associated with the stand were recorded. The stand boundaries indicated on forest cover maps were assumed to be the true boundaries, and the geometry (plot spacing and relative position) of the grid of sample plots was determined on the map. Plot layout commenced from a known ground position (control point) and random numbers were generated in the field to establish the relative position of the first plot. Plot centres were then established by locating the sampling grid, which was done by traversing from the starting point using a Suunto engineering compass and 50 m nylon chain. Plot locations were adjusted according to pre-determined rules only if they fell outside of the stand boundary or on roads. Plots that appeared to fall partially on skid trails were not moved. The BEC zone and subzone were determined from maps and during the traverse field-checked at each plot by consulting the appropriate BEC field guide (Braumandl and Curran 1992).

A wooden stake was driven into the ground at each plot centre, and marked with the stand and plot number. A series of biophysical attributes were measured, including continuous and categorical variables (Table 8). A soil pit was dug close to plot centre, and a complete description was made. The species and abundance of each species of competing vegetation was also recorded. Boundaries of the four 0.01 ha quadrants along cardinal bearings were established; trees in the northeast and southwest quadrants were flagged near breast height with pink tape, and trees in the other two quadrants with white. Only live trees of the species of interest, greater than 1.3 m in height, were flagged. Trees were numbered consecutively beginning with the northeast quadrant and moving clockwise. The plot, quadrant, tree number and attributes for each tree (Table 8) were also recorded.
Attribute	Description	Method or Technique
Biophysical		
Elevation	Elevation (metres above sea level)	Casio altimeter-watch calibrated daily
Slope	Approximate surface inclination (percent)	Suunto Clinometer
Aspect	Direction (degrees relative to true north)	Suunto Engineering azimuth compass
Site Series	BEC site classification	Classification according to Braumandl and Curran 1992
SMR	Relative Soil Moisture Regime	same as above
SNR	Relative Soil Nutrient Regime	same as above
Vegetation	Percent cover by species	Subjective estimation of percentage of plot area covered by a vertical projection of foliage
Tree		
Species	Scientific and common name	Subjective observation
DBH	Diameter at breast height (cm)	>5 cm: Steel diameter tape
		≤ 5 cm: hand caliper
Crown Class	Canopy position class (dominant, co-dominant, intermediate, suppressed)	Subjective observation

Table 8. Description of plot level attributes and measurement method or technique.

### 3.3.2 Phase 2

The selection and identification of sub-sample trees was made before returning to field plots for sampling. All tree measurements made in the first phase were entered into a Microsoft Excel97 spreadsheet database. A small program was written to select second-phase sample trees from this database. This program made two sample tree selections for each site/plot/quadrant/species combination. First, the three largest diameter dominant or co-dominant trees were selected from the pool of trees of that species present on the quadrant. Only one of these trees was intended to be chosen as the top-height sample tree; however, the identification of three trees allowed the field crew to reject up to two trees with unacceptable attributes (such as damage or evidence of past suppression) before rejecting the species on that quadrant entirely. Secondly, one tree was selected randomly from the pool of trees of that species present on verlaps the AHT population, it was possible for a given tree to be selected as the sub-sample tree for both populations. Lists of these trees were written to an output file that could be formatted as a data collection form for use in second phase sampling. Plots were re-visited and each selected THT and AHT tree measured for height, past height where possible, height to the base of the live crown, total and BHA (Table 9).

Attribute	Description	Method or Technique
1995 Height	Total tree height above ground (cm) at the end of the 1995 growing season	≤ 7 m: telescoping height pole >7 m: Criterion Laser survey tool
Past Height	Total tree height above ground (cm) at the end of each previous growing season as far back as could be measured reliably	same as above
Total Age	Total number of rings present at the end of	By ring count in the field aided by hand lens:
	the 1995 growing season, taken as close as possible to the germination point	≤ 4 cm by felling > 4 cm by increment core
BH Age	Total number of rings present at the end of the 1995 growing season, taken at 1.3 m above ground	same as above

Table 9. Description of tree level attributes and measurement method or technique.

### 3.4 DATA PROCESSING

Data processing was performed using Microsoft Excel and Access (both versions 5 and 97) and the SAS System (version 8) under Windows NT4. All data were recorded at the plot on waterproof paper, and entered into Microsoft Excel electronic databases shortly thereafter. This helped ensure that errors (both measurement and entry) were identified promptly, while the data were fresh and the field crew had the opportunity to return to sample plots to reconcile discrepancies. After field sampling was complete, the paper and electronic versions of the entire data set were compared manually to identify further errors. The stand, plot and tree level data were then combined into a single database in Microsoft Access97 format. This formed the base data set on which all subsequent analyses were made.

Data summaries were generated for stand, plot, and tree attributes to help identify unusual observations and possible errors. Height trajectories (height against age) were also plotted by species and stand. Age and development were compared within plots and stands and to known disturbance history to identify advance regeneration and veteran trees that require special attention.

Several variables important in this analysis were derived. The number of years to reach breast height is equivalent to the number of rings at the point of germination less the number of rings at breast height, plus 1. YTBH was calculated for each tree in this way (for both the THT and AHT populations) using age measured from increment cores. Age measurements were assumed correct; where age was unavailable (due to rot or error) a YTBH value for the tree was omitted. Also, age at the end of the 1995 growing-season (associated with total height) was the only age measured. For trees with multiple height measurements, ages at past height points were derived by subtraction. It was assumed in this calculation that annual nodes were correctly identified, and, therefore, the ages attached to points in height using this method were also correct.

In addition, some independent variables were transformed to create new variables for use in regression analysis (Table 10). Some transformations were chosen to linearize relationships between variables. Others were chosen to represent *a priori* hypotheses about relationships between variables.

Variable Name	Formula	Description
elev	= elevation	elevation scaled to thousands of metres
elev2	= elevation <sup>2</sup>	as above, squared
slope	= slope	slope as recorded
slope2	= slope <sup>2</sup>	as above, squared
plotSI	= mean plot SI	average of SI estimates for a species at the plot level using the appropriate Province of B.C. GI model (Nigh 1999)
plotSI2	= (mean plot SI) <sup>2</sup>	as above, squared
standSl	= mean stand site index	average of SI estimates for a species at the stand level using the appropriate Province of B.C. GI model (Nigh 1999)
standSI	= (mean stand site index) <sup>2</sup>	as above, squared
standBA	= mean stand basal area	average basal area per hectare for all trees at the stand level
standBA2	= (mean stand basal area) <sup>2</sup>	as above, squared
standSPH	= mean stand density	average tree density (stems per hectare) for all trees at the stand level
standSPH2	= (mean stand density) <sup>2</sup>	as above, squared
plotBA	= mean plot basal area	average basal area per hectare for all trees at the plot level
plotBA2	= (mean plot basal area)²	as above, squared
plotSPH	= mean plot density	average tree density (stems per hectare) for all trees at the plot level
plotSPH2	= (mean plot density) <sup>2</sup>	as above, squared
contasp	$= 1 + \cos(\text{aspect-45})$	aspect transformed into a linear index of "northeastness"
casl	= cos(aspect)·slope	transformations of slope and aspect to represent annual solar gain ( <i>sensu</i> Stage 1976)
sasl	= sin(aspect)·slope	same as above
slasp	= slope-aspect	linear interaction between slope and aspect

Table 10. Summary and calculation of transformed and derived independent variables.

### 3.5 **REGRESSION ANALYSIS**

All regression analyses were done using the SAS System Version 8 under Windows NT4. The SAS REG procedure (SAS Institute Inc. 1989) was used to fit linear models. The Marquardt method of the SAS NLIN procedure was used for fitting non-linear models. All significance tests were conducted at the  $\alpha$ =0.05 level. Each stage in model fitting was assessed using scatter plots of residual against predicted values and against independent variables. Residual plots were examined for apparent bias, non-linearity, variance homogeneity and potential outliers. Models were compared using R<sup>2</sup> and RMSE, where appropriate.

## 3.6 YEARS TO BREAST HEIGHT MODELLING

Initially, all possible combinations (in contrast to stepwise or other selection methods) of continuous predictors were considered. Models were fit for all possible combinations of predictors and Mallows'  $C_p$  statistic (Neter *et al.* 1996; Cook and Weisberg 1999) determined for each combination. Because models of every possible combination are produced,  $C_p$  is best used to filter the worst models, rather than to select the best model (Cook and Weisberg 1999). Initial evaluations using  $C_p$  were chosen over other methods because they appeared most efficient.

Exploratory analyses suggested that usually only one or two models with the smallest  $C_p$  were significant. Therefore, to limit the number of combinations under consideration to a manageable sized set, only the five combinations of predictors with the lowest  $C_p$  were given further consideration. The model with the lowest  $C_p$  was selected as a starting point and was refit repeatedly with predictors removed or re-introduced to determine a combination of predictors that were significant and also resulted in a significant model. Once the best model using continuous predictors was identified, categorical predictors were introduced as dummy variables to generate a unique intercept for all data in the category.

## 3.7 **HEIGHT YIELD MODELLING**

Two approaches were used to develop height yield models. The first was a two-stage parameter prediction approach (Clutter *et al.* 1983), which was used only for trees with repeated measurements. The intended outcome of this approach was a set of models that would address the general objectives of this research. In addition, this approach would show which variables appeared useful in explaining variability in height yield, assisting in further modelling. The alternative approach was to include the independent variables *ad hoc* and compare competing models using fit statistics and whole-model F tests. In both cases, a base model form was required first, before including independent variables.

### 3.7.1 Base Model

The base model describes the general trend with age, and was modified by the inclusion of additional independent variables to increase precision. Plots of height trajectories were examined to identify mathematical functions (models) that produced similar forms. A review of the literature

was also completed to identify functions that been used in other analyses (see Section 2.6). A set of the most promising models was produced for testing. The Chapman-Richards (C-R) model was included because it produces sigmoid curve forms that are biologically meaningful over a greater range of ages than exponential or power models. Some models were linear or intrinsically linear and were possible to fit using linear regression under appropriate transformations.

Models of each form were fit to each tree using the appropriate regression technique. However, annual height growth can be variable; short trajectories do not represent average trends. Fitting models to a limited number of individual points is technically difficult and of little practical use. Therefore, only trees with five or more measurements per tree were used for exploring base models. Scatterplots of residual against predicted values were generated across all trees by species and model and examined for lack of fit, variance problems, and unusual observations. Average RMSE was also calculated by model. Comparisons were made between models, and a subset of models selected for further investigation using these summaries.

#### 3.7.2 Parameter Prediction

The parameter prediction method was completed in two steps. First, the base models were fit to each tree with five or more measurements. This limited the parameter prediction method to the THT population, as only single measurements were made on AHT trees. For each species, each estimated coefficient was placed in a scatterplot matrix against the independent variables. This were done to identify possible relationships, outliers, and non-linearity that suggested transformation of independent variables.

The parameter prediction equations for each base model coefficient were developed by first considering all possible combinations (in contrast to stepwise or other selection methods) of continuous predictors. Models were fit for all possible combinations of predictors and Mallow's  $C_p$  statistic determined for each combination. Models with the five combinations of predictors with the smallest  $C_p$  were identified. The model with the smallest  $C_p$  was selected as the starting point for model refinement. From this point, each model was refit with additional predictors or with others removed or re-introduced to determine a combination of predictors that were significant and also resulted in a significant model. The results were examined for apparent trends to guide further analysis.

The final models were developed by substituting the parameter prediction equations into the respective base models. Each coefficient was then simultaneously estimated across all data for each of the five species. For the non-linear models fit using PROC NLIN, the parameter estimates from the first step were used as starting values. Resulting models were compared using the R<sup>2</sup>, RMSE. Model fit was assessed using scatter plots of residual against predicted values and against independent variables. On the basis of these comparisons, the best base model was selected for further analysis.

#### 3.7.3 Ad hoc *Modelling*

Two *ad hoc* approaches were used to include site differences in the base model. Both involve replacing base model parameters with linear functions of site variables. This approach differs from the parameter prediction method because the choice of independent variables to model was arbitrary. In the first approach, coefficients were expressed as linear functions of one or more of slope, aspect and elevation, in all possible combinations. These models are called "site variable" models. In the alternative approach, SI is used instead of slope, aspect and elevation. These models are called "SI" models. Because the site variable models were more complex (involved three variables), only the scale parameter (see Section 2.6.4) was analyzed.

In both approaches, models were fit to the data pooled across all observations by species and by population. The result was a series of nested models; for the site variable models, each model simpler than the full 3-parameter model is a subset of the full model. The nesting is extended to 1-parameter models that are subsets of the respective 2- and 3-parameter forms. For the SI models, models were simpler when one or more coefficients were not expressed as functions of SI. By the same argument, the base model is nested in all models.

Resulting models were compared using R<sup>2</sup> and RMSE. Scatter plots of residual against predicted values were examined for lack of fit, variance homogeneity and possible outliers. Whole model F tests were performed (by species and population) at each level of nesting to determine whether the improvement in RMSE associated with a more complex model was statistically significant (Neter *et al.* 1996; Cook and Weisberg 1999). For a given test, the null hypothesis is that the reduced (nested) model is adequate; the alternative hypothesis is that the more complex model is superior. The F statistic was calculated as:

$$F_{(df_D, df_A)} = \frac{\left(SSR_R - SSR_A\right) / \left(df_R - df_A\right)}{SSR_A / df_A}$$

where  $SSR_R$  and  $df_R$  are the residual sums of squares and degrees of freedom for the reduced model, and  $SSR_A$  and  $df_A$  are the same statistics for the full model. In this thesis, terms in the numerator are called "difference" and terms in the denominator "full"; *i.e.*,  $df_R$ - $df_A$  is the "difference degrees of freedom" ( $df_D$ ). For a given species and population, the best model possessed two attributes:

- 1. the lowest RMSE between models significantly different from the base model; and,
- 2. statistically-significant improvement over simpler (nested) models using a subset of the same independent variables.

# 4. **RESULTS**

## 4.1 SITE SUMMARY

The majority of field data were collected in a single four-month period. The time available for sampling and the complexity of the design limited sampling to 53 plots over nine sites (Table 11). Each site is identified uniquely by polygon number. A range of elevation, aspect and slope were captured, but some combinations were missed. For reference, the mean level of Kootenay Lake is approximately 550 m above sea level (asl).

Forest Cover	Polygon	BEC	Elevation	Aspect	Slope
Map Sheet	Number	Subzone	(m asl)	(degrees)	(percent)
82F-053	283	ICHmw2	1248	122	15
82F-053	297	ICHdw	923	104	27
82F-064	212	ICHmw2	1235	68	53
82F-064	490	ICHdw	973	105	26
82F-065	592	ICHmw2	1362	109	44
82F-065	609	ICHdw	928	147	25
82F-066	106	ICHdw	906	57	27
82F-066	525	ICHdw	647	68	6
82F-076	524	ICHmw2	1343	153	47

Table 11. Biophysical attributes of study sites.

A variety of silvicultural treatments were identified on sample sites (Table 12). The calendar year of treatment was noted where available from forest cover mapping or Ministry of Forests databases; however, the lack of record does not imply a treatment had not been applied. At least one stand (490) had been planted more than once.

Polygon	Logged	Burned	Planted	Top Height	Weeded	Juvenile	Pruned
Number				Establishment		Spaced	
524	1964			1968		1991	1992
106	1967	1968		1971		1985	
212	1970		1973	1975			
592	1972	1973	1974	1976		1996	
525	1974			1976	1978		
609	1981	1983	1986	1981	1986		
283	1983	1983	1985	1982			
297	1983	1986	1987	1986	1987		
490	1983	1984	1990	1988			

Table 12. Treatment history and calendar year of study sites.

Note: "top height establishment" is the year at which mean total age of top-height trees was zero. This may differ from planting year where planting stock was 1 or 2 years old, or because stands were planted multiple times and only the first year of planting is recorded.

#### 4.2 YEARS TO BREAST HEIGHT MODELLING

#### 4.2.1 Data description

Years to breast height data were pooled for use in modelling (*i.e.*, the sampling design was not explicitly considered during model development). As a consequence, simple summary statistics may be biased. Interpretation of the YTBH data and the results of data analysis should be made in consideration of this possibility.

Data were collected for more species and more data were collected for a given species in the AHT population, although they were sampled from the same plots. This was not surprising, because the THT definition was far more restrictive than the AHT definition.

Summaries of the data used to fit years to breast height (YTBH) models are shown in Table 13 and Table 14. Some trends are apparent in these summaries. Fewer data were available for THT than for AHT trees. YTBH for top-height trees was less variable for all species except western larch and paper birch. The intolerant species (*e.g.*, paper birch, lodgepole pine, western larch and Douglas-fir), usually regarded as fast growing, had the lowest average YTBH, while the tolerant species (*e.g.*, western redcedar, grand fir and subalpine fir) had the highest average YTBH.

		Number of years to breast height									
Species	Number of Observations	Minimum	Maximum	Mean	Standard Deviation						
Bl <sup>6</sup>	26	7	14	10.38	2.30						
Bg	35	3	17	9.06	3.02						
Sx	49	4	21	8.73	2.78						
Pw	53	3	18	8.62	2.79						
Lw	63	3	10	5.65	1.70						
Pl	65	3	8	5.23	1.22						
Ep	82	2	12	4.06	1.75						
Hw	95	3	18	8.42	3.20						
Cw	97	4	18	9.39	3.31						
Fd	160	4	17	7.84	2.21						
All species	727	2	21	7.54	3.09						

Table 13. Average-height tree years to breast height data summary.

<sup>&</sup>lt;sup>6</sup> For clarity, Province of British Columbia, Ministry of Forests tree species codes are used in tables and figures. Scientific and common names and corresponding species codes are given in Appendix I.

		N	umber of years t	o breast height	
Species	Number of Observations	Minimum	Maximum	Mean	Standard Deviation
Bg	17	3	14	9.24	2.70
BI	18	7	14	9.61	1.65
Sx	28	4	13	7.68	2.09
Pw	37	4	15	8.22	2.41
Pl	51	3	7	4.71	0.94
Cw	53	5	16	8.21	2.60
Lw	54	2	10	5.39	1.86
Ep	73	2	12	3.84	1.76
Hw	76	2	14	7.39	2.68
Fd	129	4	15	7.33	1.93
All species	536	2	16	6.72	2.66

Table 14. Top-height tree years to breast height data summa	Table 14.	Top-height tree	years to breast	height data	summary
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Data for both THT and AHT populations were poorly distributed between stands (Figure 3 and

Figure 4). For example, for every species (except Douglas-fir) and for both THT and AHT populations, at least 20% of the data came from a single stand, and at least 50% from just two stands. On some stands (such as Stand 535 or 283), six or seven species were present with similar abundance. On other stands (such as Stand 490 or 297), one or two species dominated.



Figure 3. The distribution of average height YTBH data by species and stand.



Figure 4. The distribution of top-height YTBH data by species and stand.

Scatterplot matrices of YTBH, slope, transformed aspect, elevation, average stand SI, and average stand BA showed little obvious relation between variables for any measured species. Scatterplots for both average and top-height trees for Douglas-fir had the most data points and are characteristic of all other species (Figure 5 and Figure 6).

Trends in mean YTBH and the distribution of observations across categorical variables were also inconsistent. For grand fir, western redcedar, Douglas-fir, and western larch, mean YTBH decreased with increased moisture (increased SMR) (Table 15). For the remaining species, there were either no trends or trends to increased YTBH with increased moisture. Most observations were on mesic (SMR 4) or slightly dry (SMR 3) sites, however. Trends in mean YTBH across SNR classes were also inconsistent, with data concentrated on nutrient medium sites (Table 16). Trends across site series are difficult to discern because site series integrates moisture, nutrients and potentially other factors in terms of expressed vegetation. Furthermore, the majority of the observations were on the two mesic site series in each BEC subzone (01a and 01b in the ICHdw and 01 and 04 in the ICHmw2) (Table 17).

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Figure 5. Douglas-fir years to breast height scatterplot matrix (average-height trees). YTBH is years to breast height, Slope is in percent, aspect is transformed to a continuous index of northeastness, elevation is in metres, stand SI is stand-average site index in metres BHA<sub>50</sub>, stand BA is stand-average basal area in m<sup>2</sup>·ha<sup>-1</sup>, and stand SPH is stand-average density in st·ha<sup>-1</sup>.



Figure 6. Douglas-fir years to breast height scatterplot matrix (top-height trees). YTBH is years to breast height, Slope is in percent, aspect is transformed to a continuous index of northeastness, elevation is in metres, stand SI is stand-average site index in metres BHA<sub>50</sub>, stand BA is stand-average basal area in m<sup>2</sup>·ha<sup>-1</sup>, and stand SPH is stand-average density in st·ha<sup>-1</sup>.

	Number	of Obser	vations b	y SMR cla	Mean by SMR class							
Species	2	3	4	5	7	2	3	4	5	7		
Bg		12	13	10			9.7	9.5	7.7			
Bl		12	7	5	2		10.5	9.7	10.2	12.5		
Cw	1	35	51	6	4	10.0	9.9	9.3	8.5	8.0		
Ер	3	27	31	20		4.0	3.5	4.3	4.1			
Fd	4	53	86	17		7.3	8.9	7.4	6.8			
Hw	1	30	50	8	2	4.0	7.8	8.7	7.3	7.0		
Lw	1	19	32	11		6.0	6.7	5.3	4.9			
Pl	8	22	28	7		5.3	5.4	5.3	4.4			
Pw	1	26	20	5	1	7.0	9.6	7.7	8.0	7.0		
Sx		13	29	7			8.5	9.0	8.1			

Table 15. Average-height tree YTBH data summary by Soil Moisture Regime (SMR) class.

Note: The definition of SMR classes 3, 4, 5, and 7 follow Braumandl and Curran (1992). No observations were available (n/a) for some species and SMR class combinations.

	Number of Ob	servations by SNI	R class	Mean by SNR class						
Species	poor	medium	rich	poor	medium	rich				
Bg	9	25	1	9.9	8.9	6.0				
Bl	1	21	4	14.0	10.1	11.0				
Cw	20	75	2	9.8	9.4	6.0				
Ер	26	54	1	3.6	4.1	6.0				
Fd	32	121	7	9.3	7.6	5.6				
Hw	19	71	1	7.6	8.3	8.0				
Lw	17	45	1	6.7	5.3	4.0				
PI	25	37	3	5.2	5.4	3.7				
Pw	24	29		9.5	7.9					
Sx	1	45	3	10.0	8.7	8.7				

Table 16. Average-height tree YTBH data summary by Soil Nutrient Regime (SNR) class.

Note: The definition of SNR classes poor, medium, and rich follow Braumandl and Curran (1992). No observations were available (n/a ) for some species and SNR class combinations.

#### 4.2.2 Independent Variables

Most independent variables collected were tested as predictors of the number of years to reach breast height. Tested variables and transformations were those presented in Table 10; in addition, soil moisture regime was included in the form of three classes: DRY (SMR 2 or 3), MOIST (SMR 4 or 5) and WET (SMR 6 or 7).

,	No. of	ations b	y BEC Z	Zone an	d Site S	eries	Mean by BEC Zone and Site Series							
	ICHe	dw		IC	Hmw2			ICH	dw		Ю	CHmw2		
Species	01a	01b	01	03	04	05	09	01a	01b	01	03	04	05	09
Bg	9	16	3		4	3		9.9	8.3	9.3		9.8	9.3	
Bl	1		13	3	2	5	2	14.0		9.9	11.7	8.0	10.2	12.5
Cw	20	22	21	11	17	2	4	9.8	10.0	7.9	9.5	10.6	6.0	8.0
Ep	26	47	3		3	2		3.6	3.7	6.3		6.3	6.5	
Fd	32	51	30	14	27	6		9.3	7.2	7.8	8.7	7.1	6.8	
Hw	19	19	22	6	20	3	2	7.6	8.6	8.0	9.3	8.4	7.7	7.0
Lw	17	29	2	2	13			6.7	4.9	6.0	6.0	5.8		
Pl	25	17	10		11	2		5.2	5.1	6.1		5.0	4.0	
Pw	24	13	5		9	1	1	9.5	8.8	8.4		6.2	10.0	7.0
Sx	1	6	17	4	14	7		10.0	8.7	8.2	9.3	9.4	8.1	

Table 17. Average-height tree YTBH data summary by BEC Site Series.

Power transformations of several predictors were included, because scatter plots suggested some non-linearity between independent variables (*e.g.*, Figure 5). Others were chosen to represent *a priori* hypotheses about relationships between variables. Stand or block SI was not available for every observation. This occurred where a top-height tree of the species of interest was not present on the plot or stand, meaning SI estimates could not be derived. Models using these two predictors had fewer observations, as those without SI had to be discarded.

While herbaceous and shrubby vegetation data were available, they were not used in regression analysis. Site Series (a categorical variable) was also not used. Both of these variables showed no apparent correlation to YTBH or other predictors in exploratory scatterplots. Variability in YTBH was also highest across these predictors. Furthermore, most sites had received vegetation control treatments either at establishment or subsequent to establishment, the timing and magnitude of which was difficult to discern and not aggressively investigated during data collection. Meaningful modelling of the retrospective relationship between YTBH and vegetation under these conditions was nearly impossible.

### 4.2.3 Model Fitting

AHT data were analyzed first, because more data were available for this population. The results from AHT analysis are similarly presented first.

# 4.2.3.1 Average-height trees

Two different YTBH model forms were produced for average-height trees (Type 1 and Type 2). Type 1 involves only site attributes (such as slope, aspect, elevation and SI) while Type 2 included site and stand parameters (such as stand BA or SPH). The models including stand parameters are presented separately because they may be interpreted differently. Statistically significant Type 1 models were produced for subalpine fir, paper birch, Douglas-fir, and western larch. For grand fir and lodgepole pine, a significant model of either type could not be developed. For the Type 1 (site) model, the final form was:

$$YTBH' = b_0 + b_1 \cdot SLOPE + b_2 \cdot SLOPE^2 + b_3 \cdot ELEV + b_4 \cdot ELEV^2 + b_5 \cdot SI_{STAND}$$

where *YTBH*' is predicted YTBH and  $b_{\theta}$  through  $b_5$  are species-specific coefficients (Table 18). When one of the independent variables above was not significant at the  $\alpha$ =0.05 level for a given species, it was not included in the final model, and the coefficient may be considered zero.

Model summary and fit statistics for each species are given in Table 19. Scatterplots of residuals suggested no remaining nonlinearity, bias, or heteroskedasticity for any of the four species. In general, the data were quite variable (RMSE of 1.3 to almost 2 years) and few data points were identified as possible outliers (*e.g.*, Figure 7). As no identifiable measurement, input or analysis errors could be found for the possible outliers, these points were retained in the final analysis.

Table 18. Coefficients for the average-height tree YTBH models for Bl, Ep, Fd and Lw.

Species	b <sub>0</sub>	<b>b</b> <sub>1</sub>	<b>b</b> <sub>2</sub>	b <sub>3</sub>	b <sub>4</sub>	<b>b</b> <sub>5</sub>
Bl	13.40	-0.298	0.00483			
Ер	9.62			-15.86	10.27	
Fd	28.65			-24.43	11.21	-0.330
Lw	21.80			-33.11	16.19	

Table 19. Summary and fit statistics for the average-height tree YTBH models for Bl, Ep, Fd and Lw.

	Degrees of F	reedom			Fit Statistics		
Species	Model	Total	F Value	p	<b>R</b> <sup>2</sup>	RMSE (years)	
Bl	2	25	5.67	0.0100	0.33	1.96	
Ер	2	80	12.51	<0.0001	0.24	1.34	
Fd	3	150	12.80	<0.0001	0.21	2.02	
Lw	2	62	8.96	0.0004	0.23	1.51	



Figure 7. Example scatterplot of residual vs. predicted values for Fd average height YTBH model.

The Type 2 model was fit for western redcedar, western hemlock, western white pine and interior spruce. For these species, stand average BA or SPH were significant YTBH predictors (model p<0.01 for all four species). The best model used stand BA alone. Stand or plot SPH was not significant if included with BA. The model was:

$$YTBH' = b_0 + b_1 \cdot BA_{STAND}$$

where *YTBH*' is predicted YTBH and  $b_0$  and  $b_1$  are species-specific coefficients (Table 20).

Species	b <sub>0</sub>	b <sub>1</sub>	Species	b <sub>0</sub>	<b>b</b> <sub>1</sub>
Cw	7.45	0.230	Pw	6.42	0.319
Hw	6.38	0.230	Sx	6.56	0.299

Table 20. Coefficients for the average height YTBH models for Cw, Hw, Pw and Sx.

Scatterplots of residuals suggested no remaining nonlinearity, bias, or heteroskedasticity for any of the four species. No data points were identified as possible outliers. While significant at the  $\alpha$ =0.05 level, these models had larger residual variance than the models for subalpine fir, paper

birch, Douglas-fir and western larch (Table 21). However, the trend mirrors that shown in summary statistics (Table 13).

	Degrees of Fre	eedom		<u> </u>	Fit Statistics		
Species	Model	Total	F Value	р	R <sup>2</sup>	RMSE (years)	
Cw	1	95	6.76	0.0108	0.07	3.21	
Hw	1	90	8.83	0.0038	0.09	2.86	
Pw	1	52	13.27	0.0006	0.21	2.51	
Sx	1	48	10.68	0.0020	0.19	2.54	

Table 21. Summary and fit statistics for the average-height tree YTBH models for Cw, Hw, Pw and Sx.

## 4.2.3.2 Top-height trees

Two different YTBH model forms were produced for top-height trees (Type 1 and Type 2). Type 1 involves only site attributes (such as slope, aspect, elevation and SI), while Type 2 included site and stand parameters (such as stand BA or SPH). Different models were produced for different species; the models including stand parameters are presented separately because they may be interpreted differently.

Statistically significant Type 1 (site) models were produced for subalpine fir, paper birch, Douglasfir, western larch and western hemlock. The final model for these species was:

$$YTBH' = b_0 + b_1 \cdot SLOPE + b_2 \cdot ELEV + b_3 \cdot ELEV^2 + b_4 \cdot CONTASP + b_5 \cdot SASL + b_6 \cdot SI_{STAND}$$

where *YTBH*' is predicted YTBH and  $b_{\theta}$  through  $b_{\delta}$  are species-specific coefficients (Table 22). Where one of the independent variables was not included in the final model for a given species, the coefficient may be considered 0. Neither categorical variable (SMR or SNR) contributed significantly for any species.

Species	b <sub>0</sub>	<b>b</b> <sub>1</sub>	<b>b</b> <sub>2</sub>	<b>b</b> <sub>3</sub>	$\mathbf{b}_4$	<b>b</b> <sub>5</sub>	b
BI	-91.61	-0.287	83.46				
Ер	15.88		-29.80	17.56			
Fd	25.01		-18.22	8.62			-0.345
Lw	28.64	0.055	-27.90	13.24		-0.050	-0.436
Hw	50.59	0.083	-56.05	24.10	-1.061		-0.605

	Degrees of Freedom				Fit Statistics		
Species	Model	Total	F Value	ρ	R <sup>2</sup>	RMSE (years)	
Bl	2	16	9.84	0.0021	0.58	1.17	
Ер	2	71	16.08	<0.0001	0.32	1.24	
Fd	3	120	9.43	<0.0001	0.19	1.80	
Lw	5	51	11.66	<0.0001	0.56	1.31	
Hw	5	68	6.17	0.0001	0.33	2.17	

Table 23. Summary and fit statistics for the Type 1 top-height tree YTBH models for Bl, Ep, Fd, Lw and Hw.

Scatterplots of residuals suggested no remaining nonlinearity, bias, or heteroskedasticity for any of the five species. The data for subalpine fir was clustered at the upper extreme of elevation; however a single observation was present at the lower extreme. Because subalpine fir is very rare at low elevations the point was removed from further analysis.

Models of the Type 2 form (site and stand parameters included) were produced for subalpine fir, paper birch, Douglas-fir, western larch, western hemlock, lodgepole pine and interior spruce. A diverse array of predictors was included, but only a subset was significant for a given species. The final model was:

$$YTBH' = b_0 + b_1 \cdot ELEV + b_2 \cdot ELEV^2 + b_3 \cdot SLASP + b_4 \cdot CONTASP + b_5 \cdot SASL + b_6 \cdot CASL + b_7 \cdot SI_{STAND} + b_8 \cdot SPH_{STAND} + b_9 \cdot SPH_{STAND}^2 + b_{10} \cdot SPH_{PLOT} + b_{11} \cdot BA_{STAND} + b_{12} \cdot BA_{STAND}^2$$

where *YTBH*' is predicted YTBH and  $b_0$  through  $b_{12}$  are species-specific coefficients (Table 24). Where one of the independent variables above was not included in the final model for a given species, the coefficient may be considered 0. Neither categorical variable (SMR or SNR) contributed significantly for any species.

RMSE ranged from 0.88 m to 1.99 m (Table 25). Scatterplots of residuals suggested no remaining nonlinearity, bias, or heteroskedasticity for any of the seven species. However, little data were available for subalpine fir and interior spruce, and the data were poorly distributed. For both species, most points were clustered at the upper extreme of each predictor with three points present at the lower extreme. This situation may result in unusually strong fit statistics where the distribution is the result of chance; the models for these species should be interpreted with extra caution.

# 4.3 HEIGHT YIELD

Years to breast height data were pooled over all plots for use in modelling. The sampling design was not explicitly considered during model development. As a consequence, summary statistics are likely biased. Interpretation of the summary statistics and the results of data analysis should be made in consideration of this possibility.

Species	b <sub>0</sub>	b <sub>1</sub>	<b>b</b> <sub>2</sub>	b <sub>3</sub>	b <sub>4</sub>	<b>b</b> <sub>5</sub>	<b>b</b> <sub>6</sub>
BI	9.21			24.70	· · · · · · · · · · · · · · · · · · ·	-0.329	
Ер	-40.32	176.29	-81.03		-0.047		-1.31
Fd	16.94						-0.32
Lw	13.31				-0.111	-0.077	-0.469
Hw	11.05						
Pl	4.18				-0.019		
Sx	6.46						`
Species	<b>b</b> <sub>7</sub>	<b>b</b> <sub>8</sub>	b <sub>9</sub>	<b>b</b> <sub>10</sub>	<b>b</b> <sub>11</sub>	<b>b</b> <sub>12</sub>	<b>b</b> <sub>13</sub>
Species Bl	<b>b</b> <sub>7</sub>	<b>b</b> <sub>8</sub>	<b>b</b> <sub>9</sub> -0.00394	<b>b</b> <sub>10</sub>	<b>b</b> <sub>11</sub>	<b>b</b> <sub>12</sub>	<b>b</b> <sub>13</sub>
Species Bl Ep	<b>b</b> <sub>7</sub>	b <sub>8</sub>	<b>b</b> <sub>9</sub> -0.00394 0.00013	<b>b</b> <sub>10</sub>	<b>b</b> <sub>11</sub> -3.67	<b>b</b> <sub>12</sub> 0.170	<b>b</b> <sub>13</sub>
Species Bl Ep Fd	b <sub>7</sub>	<b>b</b> <sub>8</sub> -0.89	<b>b</b> <sub>9</sub> -0.00394 0.00013 0.00008	b <sub>10</sub>	<b>b</b> <sub>11</sub> -3.67	<b>b</b> <sub>12</sub> 0.170	<b>b</b> <sub>13</sub>
Species Bl Ep Fd Lw	<b>b</b> <sub>7</sub>	<b>b</b> <sub>8</sub> -0.89 0.33	<b>b</b> <sub>9</sub> -0.00394 0.00013 0.00008	b <sub>10</sub>	<b>b</b> <sub>11</sub> -3.67	<b>b</b> <sub>12</sub> 0.170	<b>b</b> <sub>13</sub>
Species Bl Ep Fd Lw Hw	<b>b</b> <sub>7</sub> 0.070	-0.89 0.33 -3.01	<b>b</b> <sub>9</sub> -0.00394 0.00013 0.00008 0.00025	<b>b</b> <sub>10</sub> -0.007	<b>b</b> <sub>11</sub> -3.67	<b>b</b> <sub>12</sub> 0.170 0.026	<b>b</b> <sub>13</sub>
Species Bl Ep Fd Lw Hw Pl	<b>b</b> <sub>7</sub> 0.070 0.017	<b>b</b> <sub>8</sub> -0.89 0.33 -3.01	<b>b</b> <sub>9</sub> -0.00394 0.00013 0.00008 0.00025	<b>b</b> <sub>10</sub> -0.007	<b>b</b> <sub>11</sub> -3.67	<b>b</b> <sub>12</sub> 0.170 0.026 0.022	<b>b</b> <sub>13</sub> -0.013

Table 24. Coefficients for the Type 2 top-height tree YTBH models for BI, Ep, Fd, Lw and Hw.

Table 25. Summary and fit statistics for the Type 2 top-height tree YTBH models for Bl, Ep, Fd, Lw and Hw.

	Degrees of Fre	edom	·		Fit Statistics		
Species	Model	Total	F Value	р	R <sup>2</sup>	RMSE (years)	
ВІ	3	16	6.55	0.0062	0.60	1.19	
Ер	7	67	11.45	<0.0001	0.57	1.02	
Fd	3	120	10.32	<0.0001	0.21	1.79	
Lw	5	51	12.73	<0.0001	0.58	1.28	
Hw	4	68	11.89	<0.0001	0.43	1.99	
Pl	4	50	2.85	0.0344	0.20	0.88	
Sx	1	25	24.41	<0.0001	0.49	1.55	

## 4.3.1 Error Checking

Plotting height trajectories (height against age) for trees with multiple measurements and generating summary statistics identified four types of errors. The first two types apply to trees with multiple measurements.

The first type of error involved trees with impossible trajectories. Correct measurements must show height of less than 1.3 m at BHA 0. Unfortunately, for most lodgepole pine and interior spruce sample trees, when height was extrapolated backward (along a path of similar slope) the trajectory appeared to cross BHA 0 at heights from 2 to 6 m. The most likely cause of this error is incorrectly classifying internodal branches as terminal nodes; this results in error in estimation of

age at that point of height and at points below, because age at each height was determined by subtraction. Since no objective method for correcting these measurements could be made, only the most recent (1995) measurement for lodgepole pine and interior spruce were retained.

The second type of error was similar to the previous type, but subtler. The plotted trajectory of many trees (of different species and sites) either crossed 1.3 m in height, or appeared likely to cross 1.3 m in height, at ages close, but not equal to, BHA zero. There are two possible causes for this error. True nodes missed or internodal branches incorrectly included would result in error in estimation of age at that point of height and at points below. Alternatively, error in BH age measured from the increment core would produce error in the estimate of age at each point of height measurement.

When plotted, node mis-identification appears as unusual rates of height growth at certain ages. The consequence of age errors is the "shifting" of the entire trajectory, as the error applies to the age estimate at each point of height measurement. Comparisons were made between height trajectories of problem trees and of other trees of that species on the same site. Unfortunately height trajectories of all trees were highly variable and no objective means of identifying the point of error could be determined.

Retaining measurements of height (the dependent variable in this analysis) that contain error in age (the independent variable) violates a classic assumption of linear regression, namely that the independent variables are fixed and measured without error (Neter *et al.* 1996). However, the implication of retaining a stochastic independent variable rests on whether the independent variable "is or is not independent of the disturbance  $\varepsilon$ , and if dependent, what is the nature of the dependence" (Kmenta 1986). After some consideration the measurements were retained for the analysis despite the known error.

The third type of error involved top-height trees that appeared to be advance regeneration. When total age (or even BHA) was compared to disturbance year, a number of trees were revealed as substantially older than the stand history would suggest. Where sampled as part of the top-height population, these measurements were discarded. However, where they formed part of the AHT sample they were retained.

The fourth and final type of error was height observations with missing total or BHA. This occurred occasionally because of damage or decay. These measurements were discarded from analyses where they were required, but otherwise retained. For example, a tree with missing total age could not be used to determine YTBH, but could still be useful for top-height modelling.

## 4.3.2 Data Description

The number of trees sampled and the number of measurements per tree was diverse across species and sites. For the top-height population, multiple measurements were made on each grand fir, subalpine fir, Douglas-fir, western larch and western white pine sample tree (Table 26). Only one observation per tree was made for western redcedar, paper birch, and western hemlock. For species with multiple measurements, the sample size ranged from 986 measurements from 135 trees for Douglas-fir to 132 measurements from 18 trees for subalpine fir. For the other species, the number of trees ranged from 80 for western hemlock to 28 for interior spruce. Almost 70% of the measurements were at BH age 10 or less.

		No. Observations by BH Age Class								Std Dev
Species	es No. Trees				Total No. Obs	No. Obs	No. Obs per tree			
		2.5	7.5	12.5	17.5	22.5	27.5+			
Bg	18	52	44	23	13			132	7.3	2.79
B	18	60	69	8	5			142	7.9	1.75
Cw	67	7	17	18	12	8	5	67	1.0	n/a
Ер	74	13	51	9	1		•	74	1.0	n/a
Fd	135	313	266	196	155	53	3	986	7.3	3.22
Hw	80	9	27	20	18	6		80	1.0	n/a
Lw	55	168	112	30	14	2	1	327	5.9	2.56
Pl	51	18	18	8	7			51	1.0	n/a
Pw	37	124	102	13				239	6.5	2.94
Sx	28	2	5	12	6	3		28	1.0	n/a

Table 26	Number of trees a	od number of	f observations t	for the ton-hei	abt population
able 20.	interior trees a	iu number o	i observations i	ior the top-ne	igni population.

Note: "No." is number; "No. Obs" is number of observations. "Std Dev" is standard deviation, and is not available (n/a) for those species with only one measurement per tree.

The data for a species were also unequally distributed across stands (Figure 8). Douglas-fir, western redcedar and western hemlock were the most evenly represented, while the majority of data for subalpine fir, western white pine and interior spruce were collected from a single stand.

Results for the average-height population were similar to those obtained for the top-height population. Because the AHT population included all trees, trees in the THT population could also be included in the AHT population. Multiple measurements were not collected on AHT trees; however, where a THT sample tree was also an AHT sample tree, multiple measurements were available (Table 27). For species where this occurred, the sample size ranged from 414 measurements from 165 trees for Douglas-fir, to 102 measurements from 26 trees for subalpine fir. For the other species, the number of trees ranged from 110 for western redcedar to 49 for interior spruce. More than 74% of the measurements were at BH age 10 or less, with less than 2.5% over BH age 20.



Figure 8. Distribution of measurements by species and stand for the top-height population.

and the second	and a second		No. Obse	ervations	by BH Ag	e Class			Mean	Std Dev
Species	No.				, .			Total	No. Obs	No. Obs
	Trees							No. Obs	per tree	per tree
		2.5	7.5	12.5	17.5	22.5	27.5+			
Bg	36	37	42	22	9			110	3.1	3.58
BI	26	40	47	8	6	1		102	3.9	3.44
Cw	110	13	51	26	12	4	4	110	1.0	n/a
Ep	83	21	56	5	1			83	1.0	n/a
Fd	165	153	137	73	40	10	1	414	2.5	3.01
Hw	103	9	47	27	14	3	3	103	1.0	n/a
Lw	64	88	77	24	8	2	1	200	3.1	3.10
Pl	62	28	20	5	9			62	1.0	n/a
Pw	53	63	47	8				118	2.2	2.54
Sx	49	5	20	12	9	3		49	1.0	n/a

Table 27. Number of trees and number of observations for the average-height population.

Note: "No." is number; "No. Obs" is number of observations. "Std Dev" is standard deviation, and is not available (n/a) for those species with only one measurement per tree.

The AHT data for a species were also unequally distributed across stands (Figure 9); however the distribution appeared more even than that for the THT sample. Douglas-fir, western redcedar and western hemlock were the most evenly represented, while for subalpine fir and interior spruce the majority of data were collected from a single stand.



Figure 9. Distribution of measurements by species and stand for the average-height population.

### 4.3.3 Base Model

Sit and Poulin-Costello (1994) cataloged a wide range of curve forms that may be suitable for model fitting. Additional forms were identified in the catalog that appeared potentially suitable for modelling the trends observed in charts of height trajectories. A number of potential model forms were identified in the literature review, all of which are described by Sit and Poulin-Costello. From these sources, an initial set of models were selected for testing as base models (Table 28). The first-degree polynomial (a straight line) was included because height trajectories were often very linear on exploratory plots. The Type II Combined Exponential and Power Function though listed here and used by Thompson (1996), was not tested because of the similarity to the Type I function.

The base model data set included measurements for grand fir, subalpine fir, Douglas-fir, western larch and western white pine. Only these three five species had repeated measurements in general, as well as trees for which at least five measurements were taken. The least data were available for grand fir and subalpine fir, with only 14 and 16 trees, and 118 and 134 measurements, respectively (Table 29). The data for grand fir and subalpine fir were poorly distributed; the subalpine fir data especially divided into two clusters at extreme ages. Results for

these two species should be interpreted with great caution as they may reflect artifacts of poor data distribution.

<b>Function</b> (after Sit and Poulin-Costello 1994)	Abbreviation	Mathematical Form	Used for Juvenile Model by
First Degree Polynomial	line	$Y = a + b \cdot X$	
Second Degree Polynomial	parabola	$Y = a + b \cdot X + c \cdot X^2$	
Power	power	$Y = a \cdot X^{b}$	Omule and Krumlik (1987)
Type I Exponential	exponential	$Y = a \cdot e^{(b \cdot X)}$	Thompson (1995)
Type III Exponential	type III Exponential	$Y = a \cdot e^{\binom{b}{X}}$	Cao (1993)
Type I Combined Exponential and Power Function	combined	$Y = a \cdot X^b \cdot c^X$	Nigh (1999)
Type II Combined Exponential and Power Function	type II Combined	$Y = a \cdot X^b \cdot e^{c \cdot X}$	Thompson (1996)
Chapman-Richards	C-R	$Y = a \cdot \left(1 - e^{-b \cdot X}\right)^c$	Cao (1993)

Table 28. Potential base model curve functions. For this thesis, *Y* is height and *X* is age.

Table 29. Number of trees and observations for the base model fitting data set.

Species	No. Trees	Total No. Obs	Mean No. Obs per tree	Std Dev No. Obs per tree
Bg	14	118	8.4	2.1
BI	16	134	8.4	1.1
Fd	107	914	8.5	2.3
Lw	42	292	7.0	1.9
Pw	28	220	7.9	1.7

Note: "No." is number; "No. Obs" is number of observations. "Std Dev" is standard deviation.

The C-R model was difficult to fit to data for any species. In some cases, PROC NLIN would not converge on a solution in over 500 iterations. In other cases, NLIN would converge only if narrow bounds were placed on parameters. Even in cases where NLIN would converge, the estimated asymptote parameter was biologically infeasible, ranging from 10 to 100 m. These results are symptomatic of the limited range of the sample data, from 1 to approximately 25 years BHA. This range offers little information on the asymptotic trend; scatterplots also suggested an inflection point in height yield had not been reached. Thus, the function offered no advantage, in terms of feasibility of extrapolation beyond the range of the data used for fitting. For these reasons it was removed from further consideration.

Fit statistics for most of the six models tested indicated good fit, which was not unexpected as models were fit to individual tree height trajectories. Mean values for  $R^2$  (averaged across all trees

Model	Average R <sup>2</sup>	Average RMSE (m)
line	0.989	0.116
parabola	0.997	0.064
power	0.977	0.157
combined	0.996	0.070
exponential	0.963	0.226
type III exponential	0.978	0.170

Table 30. Average fit statistics by base model.

More dramatic differences were revealed in scatter plots of residual vs. predicted values. Scatter plots showed particularly strong lack of fit for the line and for the Type I and Type III exponential models. The remaining models, the parabola, the power and the combined models showed no strong lack-of-fit, bias, or trend in variance on scatter plots of residuals. Therefore, the line and the two exponential models were not considered further. Also, because of the similarity between the parabola and power model (and the lack of significance of one of the two terms when regression output was consulted) the parabola was also not considered further. Only the power and combined models were carried forward for further analysis.

#### 4.3.4 Parameter Prediction

#### 4.3.4.1 Data Description

The parameter prediction method was applied only to top-height trees with five or more measurements per tree. Estimated parameters for the combined and power models fit to individual trees were viewed as vectors of dependent variables. Scatterplot matrices of the parameters of the combined and power functions against independent variables revealed few obvious trends for any of the five species. The most data were available for Douglas-fir and the results are characteristic of all other species (Figure 10). Stand parameters (SPH, BA) were not included because of lack of biological and practical justification.

For the combined model, mean coefficient estimates across SMR and SNR categories showed few trends (Table 31 and Table 32). Results for the power model were similar. For example, for some species coefficient values increased with increasing SMR (*e.g.*, coefficient *a* and *c* for Douglas-fir). For other species, no trend with SMR was apparent (*e.g.*, subalpine fir and western white pine). Trends with SNR were more obvious, especially for Douglas-fir where coefficients *a* and *c* increased with SNR and coefficient *b* decreased. The data were unequally distributed between classes, however. Over 83% of observations were SMR class 3 or 4, and over 64% of observations were SNR class "medium". The distribution was particularly poor for subalpine fir and grand fir, which had the least data.



Figure 10. Example parameter prediction scatterplot matrix for parameter a of the combined model (Fd topheight trees). Slope is in percent, aspect is transformed to a continuous index of northeastness, elevation is in metres, Plot.SI is plot average site index in metres BHA<sub>50</sub>.

	a				b			С				
Species	3	4	5	7	3	4	5	7	3	4	5	7
Bg	0.100	0.060	0.165		1.862	1.962	1.340		0.907	0.986	1.075	
Bl	0.107	0.163	0.150	0.010	1.523	1.380	1.458	2.420	0.997	1.000	0.988	0.950
Fd	0.208	0.320	0.353		1.706	1.686	1.336		0.932	0.953	0.983	
Lw	0.277	0.319	0.299		1.639	1.919	2.363		0.939	0.874	0.838	
Pw	0.185	0.095	0.250	0.240	1.655	2.495	1.538	1.700	0.952	0.815	0.950	0.910

Table 31. Average values of coefficients a, b and c of the combined model by SMR class.

Note: The definition of SMR classes 3, 4, 5, and 7 follow Braumandl and Curran (1992). No observations were available for some species and SMR class combinations.

Table 32. Average values of coefficients *a*, *b* and *c* of the combined model by SNR class.

		a			b		С		
Species	poor	medium	rich	poor	medium	rich	poor	medium	rich
Bg	0.074	0.118	0.030	2.082	1.611	1.970	0.860	1.031	1.00
Bl		0.118	0.150		1.553	1.458		0.994	0.988
Fd	0.229	0.271	0.471	1.781	1.696	0.996	0.902	0.951	1.049
Lw	0.281	0.305		1.656	2.081		0.938	0.864	
Pw .	0.185	0.199		1.594	1.916		0.968	0.882	

Note: The definition of SNR classes poor, medium, and rich follow Braumandl and Curran (1992). No observations were available for some species and SNR class combinations.

### 4.3.4.2 Independent Variables

Most independent variables (see Table 10) were tested as predictors of the coefficients for each model. Stand density and basal area measures were excluded. Unfortunately, SI was unavailable for western white pine as a GI equation was not available. The SI equation was not used instead, because these models are unreliable at very young ages (*e.g.*, Nigh and Sit 1996). SMR was grouped into three classes: DRY (SMR 2 or 3), MOIST (SMR 4 or 5) and WET (SMR 6 or 7). Power transformations of several predictors were included because scatter plots suggested some non-linearity between independent variables. Others were chosen to represent *a priori* hypotheses about relationships between variables.

As with the YTBH models, herbaceous and shrubby vegetation data were not used in regression analysis. Site Series (a categorical variable) was also not used. Both of these variables showed no apparent correlation with dependent variables or other predictors in exploratory scatterplots. Furthermore, most sites had received vegetation control treatments either at establishment or subsequent to establishment, the timing and magnitude of which were difficult to discern and not aggressively investigated during data collection. Under these conditions, meaningful modelling of past height yield as a function of current vegetation was nearly impossible.

## 4.3.4.3 Parameter Estimation - Stage 1

The principal purpose of the first stage of the parameter prediction approach was to identify which independent variables were useful predictors. Therefore, model coefficients and summary statistics are not presented for this stage. In Stage 2, the resulting models were substituted into the base model and re-fit for an overall optimum, for which summary statistics are reported.

For the power function, statistically significant models were produced for at least one coefficient for Douglas-fir, western larch, and western white pine (Table 33). No statistically-significant models were produced for grand fir, subalpine fir or western larch. For the combined model, statistically significant models for base model coefficients were produced for every species (Table 34), although not for every coefficient. Scatterplots of residuals also suggested no remaining nonlinearity, bias, or heteroskedasticity for any coefficient model for the five species.

The results of the first stage of parameter prediction modelling were diverse. Trends in useful or significant predictors were not evident for any coefficient of either model. Considering the power model for example, no predictors were significant for either coefficient for subalpine fir and grand fir, or for coefficient *a* for western larch. However, the same three predictors were significant for both coefficients for western white pine. This illustrates the contrasting trends apparent within species. Some unique solutions were also produced. For the western larch power model, only two SMR classes were needed - wet sites and all others. This in effect suggests different means for the two categories. However, for the western larch combined model, six variables were significant predictors of coefficient *a*, and no variables for coefficients *b* and *c*. Plot and stand SI were also not useful for the power or combined model for any species, excepting Douglas-fir and western larch.

Species	Power Model
Вд	$a' = a_0$
	$b' = b_0$
вІ	$a' = a_0$
	$b' = b_0$
Fd	$a' = a_0 + a_1 \cdot SI_{PLOT}$
	$b' = b_0 + b_1 \cdot SI_{STAND} + b_2 \cdot SI_{STAND}^2$
Lw	$a' = a_0$
	$b' = b_0$
Pw	$a' = a_0 + a_1 \cdot CONTASP + a_2 \cdot MOIST$
	$b' = b_0 + b_1 \cdot CONTASP + b_2 \cdot MOIST$

Table 33. Final formulations of the prediction equations for the Power model.

Note: Predicted values of a and b are a' and b'. Coefficients are  $a_0$  to  $a_3$  and  $b_0$  to  $b_3$ .

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Species	Combined Model
Bg	$a' = a_0 + a_1 \cdot CONTASP + a_2 \cdot POOR + a_3 \cdot RICH$
	$b' = b_0 + b_1 \cdot CONTASP$
	$c' = c_0 + c_1 \cdot ELEV$
BI	$a' = a_0$
	$b' = b_0 + b_1 \cdot SASL$
	$c' = c_0$
Fd	$a' = a_0 + a_1 \cdot SI_{PLOT}$
	$b' = b_0 + b_1 \cdot SI_{PLOT} + b_2 \cdot SI_{STAND}^2$
	$c' = c_0 + c_1 \cdot SI_{PLOT} + c_2 \cdot SI_{STAND}^2$
Lw	$a' = a_0 + a_1 \cdot CONTASP + a_2 \cdot ELEV + a_3 \cdot SI_{STAND} + a_4 \cdot SI_{PLOT} + a_5 \cdot SI_{PLOT}^2$
	$b' = b_0$
	$c' = c_0$
Pw	$a' = a_0$
	$b' = b_0$
	$c' = c_0 + c_1 \cdot SLOPE + c_2 \cdot SASL$

Table 34. Final formulations of the prediction equations for the Combined model.

Note: Predicted values of a, b, and c are a', b', and c'. Coefficients are  $a_0$  to  $a_6$ ,  $b_0$  to  $b_2$ , and  $c_0$  to  $c_3$ .

A more diverse array of parameter prediction models was produced for the combined function. Significant parameter prediction models were produced for at least one coefficient in the case of each species. Furthermore, almost every independent variable was significant for at least one coefficient and one species. As with the power model, SI was the only significant predictor for combined model coefficients for Douglas-fir.

#### 4.3.4.4 Parameter Estimation - Stage 2

Fit statistics and scatterplots of residuals for the final fits of the power and combined models were used to make comparisons between models and species (Table 35). These statistics may be biased due to correlation of errors, either from spatial correlation of sample trees or correlation between multiple measurements on the same tree (Kmenta 1986). However, potential bias was not explicitly considered. Scatterplots of residuals suggested no remaining nonlinearly, bias, or heteroskedasticity for any models of the five species.

	R <sup>2</sup>		RMSE	(m)
Species	Power	Combined	Power	Combined
Bg	0.865	0.966	0.985	0.504
Bl	0.934	0.954	0.468	0.389
Fd	0.956	0.957	0.729	0.724
Lw	0.917	0.963	0.725	0.498
Pw	0.966	0.958	0.382	0.425

Table 35. Stage 2 parameter-prediction model fit statistics.

A noticeable trend was evident. For all species, except western white pine, the calculated R<sup>2</sup> was smaller and the RMSE was larger under the power model. High R<sup>2</sup> values were obtained, ranging from a low of 0.856 (grand fir power model) to 0.966 (grand fir combined model). Much of the magnitude of the R<sup>2</sup> values can be attributed to the high inclination of the slope; however, the relative differences are useful for comparing the fit of the different models to the same data. RMSE ranged from over 0.38 to 0.99 m, which was quite high considering height measurement was precise to the nearest 0.01 m. The greatest difference in quality of fit between models was for grand fir, with RMSE nearly double under the power model. In contrast, fit statistics were nearly constant across models for Douglas-fir.

Final model coefficients are presented in Table 36 (power model) and Table 37 (combined model). Use great care when interpreting this table, since the coefficients relate to different variables, depending on species (see Table 33 and Table 34).

Species	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>	b <sub>0</sub>	<b>b</b> 1	<b>b</b> <sub>2</sub>
Bg	0.151		··· ··· ··· ··· · · · · · · · · · · ·	1.369		
Bl	0.259			1.077		
Fd	-0.061	0.015		1.138	-0.0012	0.00013
Lw	0.592			0.936		
Pw	0.233	-0.0066	-0.100	1.300	0.072	0.171

Table 36. Stage 2 parameter prediction equation coefficients for the Power model.

Note: Where fewer parameters were included for a given model than for the largest model, some coefficients do not apply, and their values are left blank.

#### 4.3.5 Ad hoc *Models*

### 4.3.5.1 Null Model – Guide Curve

Because of the superior fit of the combined model under the parameter prediction method, only this model was carried forward for further analysis. Formal and informal comparisons of further modelling using site variables (slope, aspect, and elevation) and SI were made to a "null" model.

The null model was the combined model fit to data for a given species pooled across all stands. Since a single curve was fit, this may be considered a "guide" curve (Clutter *et al.* 1983):

$$HT' = 1.3 + a \cdot AGE^b \cdot c^{AGE}$$

where *HT*' is predicted HT. Models were significant at the  $\alpha$ =0.05 level (*p*<0.0001) for all species. Scatterplots of residuals suggested no remaining nonlinearly, bias, or heteroskedasticity for any species.

Species	a <sub>o</sub>	a1	a <sub>2</sub>	a <sub>3</sub>	a <sub>4</sub>	<b>a</b> <sub>5</sub>
Bg	0.152	-0.073	-0.048	-0.034		
BI	0.140					
Fd	-0.135	0.017				
Lw	0.542	0.00475	0.055	0.011	-0.072	1.428
Pw	0.177					
Species	b <sub>o</sub>	<b>b</b> <sub>1</sub>	<b>b</b> <sub>2</sub>		<b>C</b> <sub>1</sub>	<b>C</b> <sub>2</sub>
Bg	1.464	0.470		0.901	0.077	
BI	1.267	-0.008		0.950		
Fd	1.226	0.00546	-0.00017	1.012	-0.00171	0.00004
Lw	1.428			0.962		

 Table 37. Stage 2 parameter prediction equation coefficients for the Combined model.

Note: Where fewer parameters were included for a given model than for the largest model, some coefficients do not apply, and their values are left blank.

### 4.3.5.2 Using Slope, Aspect and Elevation

Models using only slope, aspect and elevation as independent variables (in addition to age) are called the "site variable" models. Replacing the coefficient *a* of the combined model with a linear function of site variables yielded a set of final models of the form:

$$HT' = 1.3 + (a_0 + a_1 \cdot SLOPE + a_2 \cdot CONTASP + a_3 \cdot ELEV) \cdot AGE^b \cdot c^{AGE}$$

The final model set was comprised of unique estimates of model coefficients for each species and population.

For the top-height population, RMSE comparisons and whole model F tests were useful for identifying superior models (using site variables) for all species except western redcedar and interior spruce (Table 38). Degrees of freedom, F and *p* values reported in Table 38 are those used in the whole-model F test, in which the alternative model is compared to the null model (see Section 3.7.3 for explanation). Fit statistics are for the best alternative model or for the null model where no alternative model was an improvement.

Degrees of Freedom				Fit Statistics		
Species	Difference	Full	F Value	р —	R <sup>2</sup>	RMSE (m)
Bg	2	127	60.41	<0.0001	0.932	0.703
Bl	3	136	29.59	<0.0001	0.965	0.339
Cw	'n/a	n/a	n/a	n/a	0.890	0.929
Ep	2	69	3.26	0.0442	0.720	1.122
Fd	2	981	25.98	<0.0001	0.927	0.933
Hw	2	75	5.19	0.0078	0.838	1.091
Lw	1	323	22.56	<0.0001	0.928	0.694
Pl	1	47	7.47	0.0088	0.935	0.812
Pw	2	234	12.20	<0.0001	0.961	0.406
Sx	n/a	n/a	n/a	n/a	0.841	0.907

Table 38.	Tests of site variable vs.	null models and fit statis	tics for the best THT model.
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Note: Test statistics are given for only the best model. Where no alternative model was best such statistics were not available (n/a). The terms "difference" and "full" refer to degrees of freedom used in the whole-model F test (see Section 3.7.3).

As in previous analyses, calculated R<sup>2</sup> values were high and consistent. The fit for paper birch was a notable exception as initial analyses suggested rapid, consistent growth similar to Douglas-fir. RMSE had a range similar to the parameter prediction models, with a low of 0.339 m for subalpine fir to a high of 1.122 m for paper birch. For species where direct comparisons may be made (grand fir, subalpine fir, Douglas-fir, western larch and western white pine), RMSE for the site model was equal or higher than for the parameter prediction model. Scatterplots of residuals suggested no remaining nonlinearly, bias, or heteroskedasticity for any species.

Few trends regarding which coefficients were useful were apparent from the final models (Table 39). For most species, two of the three tested predictors were included. However, for western larch and lodgepole pine only the inclusion of aspect resulted in a model significantly better, statistically. The direction of response to a given independent variable was also inconsistent; height decreased with slope for Douglas-fir and western white pine, and increased with slope for grand fir, subalpine fir and western hemlock.

Species	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>	a <sub>3</sub>	b	С
Bg	-0.072	0.00319		0.096	1.200	1.047
BI	1.188	0.00587	0.0577	-0.959	1.355	1.007
Cw	0.110				1.808	0.941
Ep	0.637		0.2942	0.081	0.899	0.969
Fd	0.327	-0.00111		0.027	1.141	1.001
Hw	0.264	0.00110		-0.088	1.609	0.941
Lw	0.456		-0.0323		1.268	0.963
Pl	0.131		0.0165		1.988	0.913
Pw	0.177	-0.00041	0.0151		1.579	0.967
Sx	0.216				1.456	0.956

Table 39. Height yield model coefficients for the site variable models of the top height population.

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Results of fitting site models for the AHT population were very similar to those for the THT population. RMSE comparisons and whole model F tests were useful for identifying superior models (using site variables) for all species except lodgepole pine and interior spruce (Table 40). Degrees of freedom, F and *p* values reported in Table 40 are those used in the whole-model F test, in which the alternative model is compared to the null model (see Section 3.7.3 for explanation). Fit statistics are for the best alternative model or for the null model where no alternative model was an improvement.

Calculated R<sup>2</sup> values were high and consistent, but generally lower than those for THT models. The fit for paper birch was again a notable exception, with the lowest R<sup>2</sup> and nearly the largest RMSE of any species. RMSE had a range similar to that for the THT models, with a low of 0.429 m for subalpine fir to a high of 1.435 m for western hemlock. Scatterplots of residuals suggested no remaining nonlinearly, bias, or heteroskedasticity for any species.

	Degrees of Fr	eedom			Fit Stati	stics
Species	Difference	Full	F Value	р	R <sup>2</sup>	RMSE (m)
Bg	1	106	30.59	<0.0001	0.865	0.955
Bl	2	97	5.52	0.0054	0.946	0.429
Cw	1	106	16.81	0.0001	0.842	1.035
Ер	1	79	4.17	0.0445	0.645	1.239
Fd	1	410	8.17	0.0045	0.920	0.844
Hw	2	98	11.06	<0.0001	0.734	1.435
Lw	1	196	21.62	<0.0001	0.909	0.775
Pl	n/a	n/a	n/a	n/a	0.943	0.735
Pw	2	113	12.95	<0.0001	0.917	0.552
Sx	n/a	n/a	n/a	n/a	0.821	1.133

Table 40. Tests of site variable vs. null models and fit statistics for the best AHT model.

Note: Test statistics are given for only the best model. Where no alternative model was best such statistics are not available (n/a). The terms "difference" and "full" refer to degrees of freedom used in the whole-model F test (see Section 3.7.3).

Few trends regarding which coefficients were useful were apparent from the final models (Table 41). Unlike the THT models, for most species only one of slope, aspect or elevation was included. The direction of response to a given independent variable was also inconsistent; height decreased with slope for western white pine, and increased with slope for grand fir and western hemlock. Similarly, height increased with elevation for paper birch, Douglas-fir and western white pine and decreased for western hemlock and subalpine fir.

Species	a <sub>0</sub>	a <sub>1</sub>	<b>a</b> <sub>2</sub>	a <sub>3</sub>	b	С
Bg	0.573	0.00343			1.164	1.027
Bl	-0.045		0.1686	-0.017	1.436	0.948
Cw	0.144		-0.0188		1.592	0.960
Ep	0.665			0.371	0.581	1.023
Fd	0.258			0.040	1.219	0.988
Hw	0.450	0.00339		-0.258	1.179	0.982
Lw	0.340		-0.0320		1.450	0.951
Pl	0.248				1.322	0.988
Pw	0.120	-0.00142		0.152	1.288	0.990
Sx	0.169				1.372	0.980

Table 41. Height yield model coefficients for the site variable models of the average-height population.

#### 4.3.5.3 Using Site Index

Models using only SI as an independent variable (in addition to age) are called the "SI" models. Replacing all of the coefficients of the combined model with linear functions of SI yielded a set of final models of the form:

$$HT' = 1.3 + (a_0 + a_1 \cdot SI) \cdot AGE^{(b0+b1\cdot SI)} \cdot (c_0 + c_1 \cdot SI)^{AGE}$$

The final model set was comprised of unique estimates of model coefficients for each species and population. An exception is western white pine, for which SI was not available; this species was not modeled.

The model was difficult to fit to data for any species when the base model coefficient *c* was replaced with a linear function of site index. Values of *c* in site variable models (Table 39) were very close to one, suggesting that the effect of this part of the combined model is relatively small. In some cases PROC NLIN would not converge on a solution in over 500 iterations, or would converge only if narrow bounds were placed on parameters. Most difficulties involved species for which the range of the sample data was limited (such as grand fir and subalpine fir) or which had relatively imprecise results in previous analyses (such as western redcedar and western hemlock). Furthermore, preliminary analyses suggested little improvement in precision when the coefficient *c* was successfully modelled. Therefore, coefficient *c* was not replaced with a function of SI in further analysis and simply estimated across all values of SI.

For the top-height population, RMSE comparisons and whole model F tests were useful for identifying superior models (using site variables) for all species (Table 42). Interpretation of tests and fit statistics reported in Table 42 is the same as that for site variable models (Table 38).

Degrees of Freedom				····	Fit Statistics	
Species	Difference	Full	F Value	p	R <sup>2</sup>	RMSE (m)
Bg	1	128	279.9	<0.0001	0.958	0.550
Bl	1	138	146.1	<0.0001	0.972	0.304
Cw	1	63	93.7	<0.0001	0.956	0.589
Ep	1	70	49.0	<0.0001	0.817	0.925
Fd	1	981	5.3	0.0214	0.956	0.726
Hw	1	76	24.1	<0.0001	0.856	1.027
Lw	1	323	288.7	<0.0001	0.959	0.523
PI	1	47	139.2	<0.0001	0.981	0.444
Sx	1	24	8.2	0.0087	0.882	0.783

Table 42. Tests of SI ver	ersus null models and fit statistic	cs for the best THT model.
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Note: The terms "difference" and "full" refer to degrees of freedom used in the whole-model F test (see Section 3.7.3).

Modelling coefficient *a* alone produced a model superior to the null model for every species. Although modelling coefficient *b* alone also resulted in statistically significant improvements, RMSE was always lower under the *a* model. In contrast, statistically significant improvements when modelling both coefficient *a* and *b* over coefficient *a* alone were rare. For the top-height population, the two-parameter model was significantly better than the coefficient *a* model in the case of Douglas-fir only. Calculated R<sup>2</sup> values were even higher than those for the site variable models. The fit for paper birch was still relatively poor, but the difference from other species was much smaller than for other approaches. The range of RMSE was similar to that for the site variable models, but lower; RMSE ranged from a low of 0.304 m for subalpine fir to a high of 1.027 m for western hemlock. Scatterplots of residuals suggested no remaining nonlinearly, bias, or heteroskedasticity for any species.

Trends between predicted height yield and SI were positive for every species (coefficient  $a_1$  always positive) in the top-height population (Table 43). The steepest trends were for western larch, lodgepole pine and paper birch; the flattest for western redcedar and western hemlock.

Species	a <sub>0</sub>	a <sub>1</sub>	b <sub>o</sub>	<b>b</b> <sub>1</sub>	С
Bg	-0.160	0.0130	1.056		1.039
BI	-0.193	0.0165	1.328		1.019
Cw	-0.016	0.0096	1.559		0.960
Ер	0.150	0.0371	0.567		1.032
Fd	-0.203	0.0194	1.501	-0.009	0.991
Hw	-0.014	0.0124	1.240		0.986
Lw	-0.378	0.0328	1.279		0.976
PI	-0.275	0.0285	1.362		0.963
Sx	-0.121	0.0166	1.288		0.981

Table 43. Height yield model coefficients for the SI models of the top-height population.

Note: If the best model did not include one or more predictors, coefficients are not available and left blank.

Similar results were produced for the average-height population. RMSE comparisons and whole model F tests were useful for identifying superior models (using site variables) for all species (Table 44). Interpretation of tests and fit statistics reported in Table 44 is the same as that for the top-height population. Modelling coefficient *a* alone produced a model superior to the null model for every species. Similar to the THT results, modelling coefficient *b* alone also resulted in statistically significant improvements. However, RMSE was always lower under the *a* model. Statistically significant improvements when modelling both coefficient *a* and *b* over *a* alone were produced for four species: grand fir, subalpine fir, paper birch and Douglas-fir. Scatterplots of residuals suggested no remaining nonlinearly, bias, or heteroskedasticity for any species.

Degrees of Freedom					Fit Statistics	
Species	Difference	Full	F Value	р —	<b>R</b> <sup>2</sup>	RMSE (m)
Bg	1	105	8.9	0.0036	0.939	0.670
Bl	1	97	7.4	0.0076	0.956	0.381
Cw	1	106	38.5	<0.0001	0.863	1.016
Ep	1	78	6.8	0.0109	0.771	1.041
Fd	1	409	28.9	<0.0001	0.933	0.779
Hw	1	99	93.2	<0.0001	0.776	1.213
Lw	1	196	167.3	<0.0001	0.945	0.606
Pl	1	58	45.7	<0.0001	0.966	0.568
Sx	1	45	66.9	<0.0001	0.911	0.816

Table 44. Tests of SI versus null models and fit statistics for the best AHT model.

Note: The terms "difference" and "full" refer to degrees of freedom used in the whole-model F test (see Section 3.7.3).

Trends between predicted height yield and SI were positive when the best model was of only coefficient *a* replaced with a function of SI (Table 45). When the best model was of both base model coefficients *a* and *b* replaced with functions of SI, the trend with one coefficient was positive and the other negative.

Table 45. Height yield model coefficients for the SI models of the average-he	eight population.
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Species	a <sub>0</sub>	<b>a</b> <sub>1</sub>	b <sub>o</sub>	b <sub>1</sub>	С
Bg	0.571	-0.0189	-0.535	0.0896	0.990
Bl	-0.423	0.0288	2.942	-0.0764	0.979
Cw	0.028	0.0158	0.096		1.011
Ер	2.308	-0.0435	-0.899	0.0437	1.092
Fd	-0.479	0.0313	2.149	-0.0353	0.984
Hw	0.001	0.0006	3.043		0.867
Lw	-0.276	0.0251	1.428		0.963
Pl	-0.101	0.0161	1.405		0.974
Sx	-0.077	0.0059	2.120		0.936

Note: If the best model did not include one or more predictors, coefficients are not available and left blank.
#### 4.3.6 Model Comparisons

For every species (where comparisons may be made), RMSE was lower under the model where the coefficients were replaced with linear functions of SI (the SI model) than under the Site Variables model (Figure 11). A comparison could not be made for western white pine because the SI model could not be fit. In some cases the reduction in RMSE approached 50%; in others the difference was marginal.



Figure 11. Comparison of RMSE between SI and site variable modelling approaches.

In contrast, comparisons between the parameter prediction models and the two alternative methods for representing site showed much smaller differences in RMSE (Figure 12). Differences between the parameter prediction and site variables model ranged from near zero to approximately 20%. Comparisons with the SI model were almost exact.



Figure 12. Comparison of RMSE between parameter prediction and *ad hoc* modelling approaches.

Comparisons of model predictions between the different modelling approaches used in this thesis and official B.C. Ministry of Forests models are difficult in the absence of independent validation data. Most models used different sets of predictors, and are not directly comparable; the SI-based models are an exception. Models for developed in this thesis for Douglas-fir had the most data and have the most promising biological behaviour, and are a logical starting point.

Comparisons between the THT and AHT models developed for Douglas-fir (Figure 13) and the official Ministry of Forests (MoF) model (Thrower and Goudie 1991) (Figure 14) show discernable differences in forecasted height. At 20 m SI the THT and AHT curves are nearly identical; at 25 m SI they diverge (the AHT curve dropping) at approximately BHA 12, and at 30 m SI they diverge at BHA 4. The AHT curve for SI 30 m drops below the AHT curve for SI 25 m at BHA 12. Comparisons between the THT curve and the MoF are more consistent, with the MoF model predicting greater height at most BHA less than 20 (Figure 14).



Figure 13. Top-height (THT) and average-height (AHT) models for Fd compared by site index.





# 5. DISCUSSION

## 5.1 YEARS TO BREAST HEIGHT MODELS

YTBH modelling was generally more successful than expected, with statistically significant models produced in some form for most species. YTBH is highly variable, from 2 to 21 years in stands sampled for this thesis, and most existing models are very imprecise (*e.g.*, Thrower and Goudie 1991). Because of this variability, the relatively small data set collected for this thesis, especially for some species, was not expected to be sufficient to discover significant effects. Nevertheless, while some of the fitted models appear surprisingly reasonable, others are clearly biologically infeasible and the artifact of limited data.

The different suites of models produced for AHT and THT trees, when including stand variables in addition to site variables, reflects the difficulty in developing YTBH models in general. Models of the first type, which included site variables only, were only produced for species either well represented in the data (*e.g.*, Douglas-fir) or poorly represented (*e.g.*, subalpine fir). Significant models were not produced for species with intermediate sized data sets. Models for subalpine fir were significant for both AHT and THT; however, they were biologically meaningless outside of the narrow range of conditions represented in the data. Models for Douglas-fir and western larch, which had relatively large data sets, were more reasonable, but still included unusual trends. For example, the AHT model for Douglas-fir predicted decreasing YTBH with increasing SI, while the THT model predicted increasing YTBH with increasing SI. In some cases, instability in coefficients because of correlations between predictors (Neter *et al.* 1996) is a possible cause. However, for other models only a single predictor (with sign opposite to expected trend) is included.

Models of the second type, which include SPH and BA as well as site variables, were even more unusual. For AHT trees, BA alone was a significant predictor of YTBH for four species (western redcedar, western hemlock, western white pine and interior spruce) for which site models could not be produced. BA was not significant in any other models when included. For THT trees, an extremely diverse array of models was produced when SPH and BA were included. Site variables that were not included previously were significant when BA or SPH were added for several species. Furthermore, some models became even more biologically meaningless.

Several pieces of evidence point to poor data distribution and problems with causal factors. These are complicated by the sampling design. For many species, SI was not available at the plot level for AHT trees because at least one THT tree of that species was not present on the plot. In these cases, many observations had to be discarded for missing values reducing the data set significantly. Nevertheless, it is possible that particular combinations of predictors may simply be unique identifiers for individual stands that do indeed posses differences in YTBH, though not attributable to the factors themselves

Firstly, SI has been popular as a measure of site quality because it integrates site factors. Yet in most models SI was not significant, with the notable exception of Douglas-fir. Instead, a wide and

diverse array of alternative predictors was included. This may be because the alternative predictors were indeed causal factors and represented variability in YTBH better than SI. The alternative predictors may also be coincident with unknown factors. Because a small number of stands were sampled, a small number of combinations of factors were represented in the data set. Secondly, many trends were inconsistent or the reverse of what would be reasonable biological behaviour. For example, stand level measures of SI, SPH and BA were significant over plot and quadrant level measures in most cases. This was true despite considerable variability between plots. This also suggests that the predictive power of the independent variables is that they uniquely identify the stand, not the actual effect of competition or site quality at the quadrant or plot level. The exception was again for Douglas-fir; however, Douglas-fir had the most data, the best representation across sites, and the greatest range in age across most independent variables measured. For Douglas-fir, the measured independent variables may themselves be the causal factors.

It is common to caution against extrapolation of regression models beyond the range of the data. However, if the trends observed are in fact the product of unobserved causal factors, defining what the range of the collected data actually is, other than the physical location of the sampled stands, may not be possible. Therefore, the models produced in this thesis are best applied only to the stands from which the fitting data were collected.

Despite these difficulties, the results have demonstrated that significant relationships can be obtained with relatively small data sets, and that they need not involve SI. In particular, the lack of significance of SI may actually be evidence that it does not integrate all factors that affect growth. This is not truly surprising since regeneration method and timing, site preparation method, size of planting stock and many other silvicultural factors are deliberately manipulated by managers to change YTBH and height yield. The lack of biologically credible YTBH model results does not support a conclusion about the role of the independent variables measured. Rather, the results suggest that the variables measured and the size of the data set gathered are insufficient to produce clear answers. The results may be interpreted to suggest that significant effects do exist, and with further research they may be identified.

## 5.2 HEIGHT YIELD MODELS

#### 5.2.1 Base Models

The results from the base model analysis were not particularly surprising, especially considering the range of ages emphasized in the data set (BHA 0 to 20). A noticeable amount of year-to-year variability in height growth was evident for most species, different from the consistent growth reported by Nigh and Love (1999) for lodgepole pine. However, this did not make discerning trends difficult for trees with 5 or more measurements. Exploratory plots of height trajectories suggested nearly linear trends, especially at BHA greater than 5; otherwise the trend was concave up and increasing, with no indication of an inflection point in the trajectory for any species. The

base model analysis supported this conclusion, as the model forms most appropriate for a curve of this shape had the best fit.

For example, height trajectories did not become smooth and consistent until approximately 5 years BHA. This result is reflective of the common belief that non-site factors (*e.g.*, brush competition) affect height in unpredictable ways until trees reach a critical height (Monserud 1985). This is echoed by the obvious lack of fit for the straight line and the two exponential models, which was concentrated at the lower extremes of BHA.

The C-R function and inverse polynomial were explored initially, because they imply asymptotic trends that are far more biologically meaningful than the long-term trends from the exponential or power functions. The inverse polynomial was not carried forward beyond exploratory analyses, because the lack of fit was severe. In contrast, the difficulty fitting the C-R model was because the age range sampled was not sufficient to establish the asymptotic trend. The C-R model was not considered further because it did not confer any advantage in representing observed growth. This decision illustrates the emphasis in this thesis on fitting the best models to the data and exploring the roles of independent variables, not in producing models with the least risk for operational application. In the latter, extrapolation is a far greater concern.

## 5.2.2 Parameter Prediction

The parameter prediction approach does not require two stages; coefficients of the base models may be replaced with functions of site variables and the entire model estimated in one step (Clutter *et al.* 1983). This approach is relatively straightforward where SI is the single site variable employed. In this thesis, a number of independent variables were available, and little information existed to guide *a priori* assumptions about which variables to include. Furthermore, fitting a large, complex parameter prediction model can be confusing, especially where non-linear regression techniques require starting values for each coefficient (Staudhammer and LeMay 2000).

The two-stage approach was used for these reasons. This allowed each coefficient to be examined individually, and simpler linear regression techniques used to efficiently explore the widest range of independent variables. By substituting the coefficient models into the base model the estimated coefficients were simultaneously re-estimated, and an optimum set of coefficients is possible. This set is conditional on the variables included, however. It is also possible that one or more variables are redundant, or that one or more variables that are useful predictors are not included because decisions about the form of the model for each coefficient were made independently.

Stand parameters (SPH and BA), BEC site series classes, and vegetation data were specifically excluded from the analysis at this point. The rationale for this decision has two parts; first, the number of independent variables under consideration even with these variables excluded was large. A limit on the extent of this analysis was arbitrarily determined to make the set manageable. Furthermore, the YTBH analysis suggested that stand and vegetation parameters were least likely to be representative of causal factors affecting height yield, and produced somewhat meaningless regression models.

The pattern of variables that appeared useful for predicting coefficients of the base models was similar to that for the YTBH analysis. A diverse array of independent variables was included, and the same variables were rarely included in models for different species. SI was reliably included in models for Douglas-fir, but not for other species. The biological feasibility of the height yield models once the coefficients were simultaneously re-estimated (stage 2) was much greater than that for YTBH models, however. For example, the scale and shape parameters (*a* and *b*) of the Douglas-fir power model were both increasing with increasing SI, suggesting higher and steeper curves on better sites. Similarly, the western white pine model parameters were decreasing with increasing contasp (degree of "northeastness") and increasing on relatively moister sites. Final models for the combined function were also biologically tenable, with minor exceptions.

The apparently greater success in modelling height yield does not completely alleviate the concern about extrapolation beyond the range of the data. For example, a consistent trend in the independent variables that explain variability was not observed, and SI was not useful for most species. Some unusual results may have been avoided by excluding stand attributes from analysis in the first instance. The significance of stand (over plot) SI in models for Douglas-fir and western larch suggests that problems associated with poor distribution may still remain. In the absence of formal validation, extending use of these models beyond the stands from which the data for fitting were collected is unwise.

Applying the parameter prediction method to the two base model forms that appeared most suitable allowed some comparison of model fit and precision. In every case but one, the combined model provided a better fit, in terms of R<sup>2</sup>, RMSE, and when scatterplots of residual against predicted values were compared. The observed difference in R<sup>2</sup> was relatively small, and scatterplots revealed only limited lack of fit for the power model at the very youngest BHA. Differences in RMSE were most striking, with a reduction of over 40% for grand fir and western larch under the combined model. The greater flexibility offered by the combined function resulted in equal, or often better fit than the simpler power model. Where the complexity does not make model fitting technically challenging, the combined function was the best choice for the data collected in this thesis.

## 5.2.3 Ad hoc Modelling

Site variables were also incorporated into base models in what was termed "*ad hoc*" modelling. The technical approach is not very different from the single stage parameter prediction method previously described; one or more of the variables in the base model were replaced with linear functions of independent variables. Since the set of variables were arbitrarily chosen (no formal technique applied to determine the largest possible useful set) the method was distinguished from the parameter prediction method. Furthermore, modelling only the *a* coefficient of the combined model was also an arbitrary decision, made principally to simplify the analysis. The decision has some biological rationale, however. Sit and Poulin-Costello (1994) note that the coefficients of the combined function interact to control the shape of the curve. But, for values of *b* and *c* greater than zero, the parameter *a* acts most closely like a scale parameter and the others as shape parameters. Where most of the difference in trajectory due to site is in scale, modelling *a* is a

reasonable assumption. This assumption was explored later in *ad hoc* modelling when SI was used as a predictor (see below).

The inconsistent trends in predicted height yield response to certain variables were disappointing, but not unexpected, given previous results. For the subalpine fir, western hemlock and western larch THT models, for example, height yield decreased with increasing elevation. For other species for which elevation was included, height increased. Where these results are due to correlations between predictors, the inability to explain more variability remains a concern. For all species but western redcedar, lodgepole pine and interior spruce, each model was a statistically significant improvement over the null model and models with more than one parameter were statistically significant improvements over models of fewer parameters, for both the AHT and THT populations. However, these tests only demonstrated that the predictors included explained part of the variability, not that the predictors were responsible for the variability.

Additional biological irregularities were introduced by allowing regression estimates of the c coefficient to be less than one. In such cases curves are initially increasing, but reach a maximum and then decline (Sit and Poulin-Costello 1994). For seven of 10 THT models, and eight of 10 AHT models estimates of c were less than one. This is likely again the result of poor data distribution, as only a few of the many combinations of slope, aspect and elevation and age were sampled for a given species. In such cases, data for the upper age ranges came from only a subset of stands, and the influence of a given stand may be greater on a portion of the curve. The flexibility of the combined model may produce more precise curves (because they fit the data better) at the expense of biological tractability. A practical alternative would be to constrain estimates of c to values greater than one.

Ad hoc models including SI alone were the most biologically reasonable models produced in this thesis. For every model where only the coefficient *a* was replaced with a function of SI, height yield predictions were increasing with increasing SI. Furthermore, in most cases R<sup>2</sup> and RMSE were lower for the SI based models. The apparent improvement in model attributes is contradictory to previous results; except for Douglas-fir, YTBH models and parameter prediction height yield models rarely included SI as a useful predictor. This contradiction is at least partially explained by the limited set of species for which the parameter prediction method may be applied, and the limited number of models in which slope, aspect or elevation were significant (as they were in *ad hoc* modelling). The two stage parameter prediction method likely did not produce the optimum combination of independent variables.

Modelling coefficient a as a function of SI alone was the best solution for 15 of 20 models. Additionally, for every species, modelling coefficient a alone produced a model with lower RMSE than models of coefficient b alone. Models of coefficient c were extremely difficult to implement, because non-linear regression would not converge or would require narrow bounds. Nevertheless, in all cases models of coefficient c were inferior to models of coefficient a. These results support the hypothesis that the greatest influence of site on model form is through a scale parameter, and that the approach used was appropriate. For the remaining five models, where some improvement was found over modelling *a* alone, while model fit was improved, models were often less biologically reasonable. For Douglas-fir, modelling coefficients *a* and *b*, for both THT and AHT, produced statistically significant improvements. The same result was found for AHT models for grand fir, subalpine fir and paper birch. For both Douglas-fir models and the subalpine fir AHT model, the effect was to flatten the trajectory with increasing SI; the effect was opposite for the other two models. The impact was also greater on AHT models. For the Douglas-fir AHT model, the curve was flattened sufficiently at large values of SI that it crossed curves for lower values of SI at reasonably young ages (Figure 13). This problem was exacerbated by values of *c* less than one, which imply an inflection and decreasing rates of growth, a result contradictory to expected performance. Following previous discussion, the flexibility of the combined model combined with poor data distribution may produce more precise curves (because they fit the data better) at the expense of biological tractability.

## 5.3 SITE INDEX AND ERROR IN PREDICTORS

With the SI system, trees themselves integrate known and unknown factors into a single index. A close feedback loop is also established between what is observed at a location and what can be predicted, especially when SI is estimated by observation and then used as a predictor for other values. This was the approach used by Nigh and Love (1999) in the development of their lodgepole pine height model. A weakness of this use of SI is that predictions become almost tautological; height and age are used to predict an index of site quality, and then age and site quality are used to predict future height. A more direct criticism is that using predictors with error violates regression assumptions. Validation with independent data would be a simple test of the assumptions inherent in this approach.

In this thesis, SI was used as a predictor in many models. Errors in age estimation were also identified during data analysis. These errors pose different problems because of their properties. Many SI models are constrained such that height is equal to SI at index age. Error in estimates of SI are correlated with age in this example, as errors increase with distance (above or below) index age (*e.g.*, Nigh and Sit 1994). When such a correlation exists, least squares estimators lose the property of consistency (Kmenta 1986). Techniques in the field of econometrics exist to generate alternative, consistent estimates; however, they were considered beyond the scope of this thesis.

In contrast, little correlation would be expected between tree age and error in age estimation from increment cores when the range of ages sampled is relatively small. This hypothesis is supported by scatterplots of height trajectories, which rarely appear more than one year in error where error is apparent. In this case, "the assumption that X is stochastic but independent of  $\varepsilon$  does not change the desirable properties and feasibility of least squares estimation" (Kmenta 1986).

## 5.4 SAMPLING DESIGN

Some weaknesses in this thesis reflect limitations imposed by the sampling design. The random selection of trees from fixed-area plots was very time consuming. Although average stand density was less than 3,800 stems per hectare (st-ha<sup>-1</sup>), many sub-plots had in excess of 10,000 st-ha<sup>-1</sup>, and one plot had in excess of 30,000 st-ha<sup>-1</sup>. A considerable amount of time was involved in identifying, tagging, measuring, and processing data from trees that had little use in the data analysis. As a consequence, the matrix of species, slope, elevation and aspect classes was not completely sampled, and some combinations had relatively few observations. While the amount of available data nearly always limits the precision possible in regression modelling, the set collected for this analysis was particularly small for exploring some combinations even with relatively poor precision.

Error in age measurement was also a disappointing result, but could be easily remedied in future work. While some error was associated with mis-identification of the points of termination of past height, in many cases it appeared that poor ring counts were the source of error. Error in ring counts would likely decrease with experience for the field crew. Furthermore, for some species (*e.g.*, paper birch), identification of rings on increment cores was inherently difficult. Reading and discarding the cores in the field (not collecting) saved some time and cost, though the opportunity to correct errors identified later was foregone.

A great strength in the design was the choice of collecting multiple measurements from individual trees though observation (non-destructive sampling). For most species, the points of termination of annual growth were easily identified, and with the Criterion laser survey tool precisely measured. Most importantly, multiple measurements per tree leveraged the number of plots sampled to substantially increase the size of the data set, at little added time or cost.

With refinement, the non-destructive technique would be even more useful. Western larch is not a species known to produce terminal whorls; however, most western larch trees measured appeared to produce one (or rarely two) nodal branches. Bud scale scars were also easily observed on close examination of relatively young trees. Because the point of termination of annual growth was reliably observed, multiple measurements were possible. However, the age of sample trees was also a factor; confidently identifying bud scale scars or nodal branches was more difficult with age. Thus, the technique would likely be less successful if applied in older stands. In contrast, lodgepole pine and interior spruce are believed to produce strong annual whorls of branches. The significant and consistent error apparent when cross-checking the field data did not support this belief. It is possible that the field crew were overzealous and with greater training and experience would produce more reliable results.

## 5.5 CAUSE AND EFFECT

Using site and stand factors as predictors to explain variability in juvenile height was a research objective for two reasons; one applied, and one basic. Developing models that are defensible on a cause-and-effect basis was important for both. In application, confidence in model predictions is

important to forest managers. Models that are defensible on a cause-and-effect basis gain biological credibility that is critical in the absence of independent data for validation (Rykiel 1995). Biological credibility also provides some confidence when models are extrapolated beyond the range of the data used in their development. In this regard, the unusual and inconsistent results from model fitting were disappointing.

In this thesis, a related objective was exploring the role of different predictors to enhance understanding of tree and stand development, based on their significance in explaining height yield. Because the analysis is not experimental, strong conclusions about site variables as if they were treatment effects on the dependent variable are difficult to draw. However, considering the results more broadly, and especially in the context of qualitative observations of stand conditions, some interpretations may be made. One possibility is that measured independent variables may also be reliable or coincident analogues for other factors. Alternative factors should be considered even when measured independent variables appear statistically significant in regression models.

## Genetics

In B.C., species selection and tree seed transfer guidelines have become more rigourous over the past 50 years. Observed growth of Douglas-fir illustrated a possible impact of this change. Douglas-fir was generally rare, but present in all four high-elevation stands (>1200 m a.s.l) sampled; however, the condition of Douglas-fir in each stand was unique. Growth and form were superior in stand 524, a small, steep, productive south aspect site that was the oldest sampled. In contrast, nearly half of the Douglas-fir top-height trees in stand 212 were initially rejected due to distorted growth and previous top damage, which appeared to have been caused by snow. Silviculture history records show that stand 212 was planted; whether an inappropriate seed source was a contributing factor to the poor growth is unknown.

#### Site Preparation and Brushing

Observed levels of competing vegetation were not explored as predictors because demonstrating a cause-and-effect relationship between the present status of competing vegetation and past growth is difficult. However, observed vegetation abundance and composition were unique on many sites, and may relate to site conditions and disturbance history. For example, snowbrush (*Ceanothus velutinus*) was present in only one stand – the same stand that was dominated by planted western larch with outstanding vigour and growth. Paper birch was common, but abundant only on moist, productive sites that had not been severely impacted by fire.

## Planting

Stocking may also be an analogue for regeneration method. Because tree planting was less common in the 1960s than the 1970s and 1980s, stands with relatively higher basal area are more likely to be older and have originated from natural regeneration. The deliberate attempt to accelerate juvenile height growth may also introduce complexity into height modelling. Though records were not uniformly available, on several sites (*e.g.*, 297 and 106) a single, dominant

species appeared to have been planted, judging from uniformity of age, size, density and spacing, especially in contrast to other species.

#### Pruning

Only one site sampled (the oldest, stand 524) had been pruned. Any direct impact of pruning on height was impossible to assess, although live crown lengths exceeded 60% on all trees suggesting impact was insignificant. However, when the field crew returned to the site for the second stage of measurements, they discovered that nearly 25% of the trees had been stripped entirely of bark on the lower bole, and nearly 50% had partial bark stripping. Given the height and nature of the damage, the stripping appeared caused by black bear (*Ursus americanus*). It is possible that the removal of the thick lower branches, and rapid growth in the thinned, productive stand made the stand unusually attractive to bear for forage. Modelling such a factor is clearly impossible, but remains a management problem despite being explicitly avoided during the development of traditional SI based height models.

## Density and Pre-Commercial Thinning

When combined with age, density is a likely analogue for silvicultural treatment. Relatively young, dense stands may be hypothesized to be less likely to have been juvenile spaced. High density in relatively old stands may suggest a pulse of natural regeneration after thinning has occurred. Because density and stocking are also analogues for time, correlation with YTBH may be due to sampling of older, suppressed cohorts. In many stands, a pulse of natural regeneration, which takes advantage of liberated growing space, follows pre-commercial thinning. Since all trees greater than 1.3 m in height were counted, stands dominated by relatively older, pre-commercially thinned trees may appear to have high stocking where natural regeneration after thinning was abundant. However, these trees clearly have developed under different competitive pressures than the overstory of crop trees.

Furthermore, in young stands, density may be correlated with YTBH because of the "chainsaw effect", instead of competition. This possibility was demonstrated at one stand. Sampling for stand 592 was completed in three stages, because in 1996 late snowmelt delayed sampling at elevations above approximately 1,000 m. Plots were located at the first visit and the stand was described as one of the most diverse mixtures visited. All species sampled for this thesis were present on the stand in more than trace abundance. When the stand was revisited for plot establishment, silviculture crews were discovered pre-commercially thinning and weeding the stand. Afterwards, examples could be found at each plot of trees in conditions that indicated they were free from past suppression – uniform growth since breast height – surrounded by stumps and debris from alder (*Alnus* spp.) and other trees that had been obvious competitors. The so-called "chain saw effect" (introduced in Section 2.5.1) was also clearly demonstrated, as the majority of trees removed were small diameter trees of lower mean height.

These examples reinforce both the evident difficulties in developing precise, sophisticated models and at the same time the potential for such models to be developed. The issue is not just a

problem of growth being inherently variable; it is a problem involving a large number of factors that determine growth variability, and the difficulty identifying, measuring and incorporating all of them. Perhaps most importantly, stands sampled in this thesis are very different, in both observed growth and in the combination of independent variables (and apparent analogues) that appeared significant.

# 6. CONCLUSIONS

Because of the high natural variability in mixed species stands, the inconsistent results of YTBH and height yield modelling were not unexpected. It is not clear whether the significant results (where found) reflect the expected cause and effect relationship between the modelled independent variables and height, or whether the independent variables were analogues for other, unknown factors. Three possibilities are:

- 1. Independent variables truly approximate causal factors;
- 2. Independent variables are analogues for alternative, unknown causal factors; and,
- 3. Combinations of independent variables are *de facto* indicators of a given site, for which causal factors are unknown or unmeasured.

Defensible relationships between the dependent and independent variables on a cause and effect basis are desirable. In the absence of validation with independent data, such arguments increase confidence when extrapolating results beyond the range of the data used in model development. Unfortunately, few such arguments are easily made for the models developed in this thesis.

Problems with cause and effect are the likely cause of significance for many YTBH models. Notable examples are the significance of stand basal area and stand density; when measured 10 to 30 years after disturbance these attributes are arguably more reflective of silvicultural history than the conditions experienced by trees when they were less than 1.3 m in height. The lack of consistent trends also does not lend credibility to the models outside of the range of the data used in their development. Since it appears that responses to independent variables are site-specific, the range of the data should be interpreted as the sites from which the data were collected.

In contrast, strong variability in YTBH was found both between and within stands, and models including combinations of independent variables were found to be statistically significant. While the models produced in this thesis have limited biological or applied justification, they do show that identifiable relationships exist. Appropriately modelling the factors that affect the observed variability in YTBH has the promise of producing much more precise models at the stand level. Such promise has not been shown for models using SI alone. An expanded data set and further analysis should address this possibility.

Height yield base model analysis was very successful at identifying functions that best suited the data, particularly in terms of the regression diagnostics. The models that appeared most suitable visually had the best fit; these were the power model and the type I combined exponential and power model. A weakness is that these models imply long-term trends that are biologically meaningless; however, models that implied asymptotic trends were otherwise problematic. An alternative would be to fit a C-R model with the asymptote parameter specified, rather than estimated. Should this analysis be extended to develop operational models, this alternative approach should be explored. Regardless, as long as interpretations and application of models based on the power or combined functions are constrained, they are biologically meaningful.

The two-stage parameter prediction approach for height yield modelling was valuable, especially when final results were compared to alternative approaches. Most notably, the method was useful as a technique to identify important independent variables as predictors of each base model coefficient. Unfortunately, few trends were observed that could form a basis for *ad hoc* modelling of species that lacked sufficient data for the two-stage approach. Moreover, the diverse and sometimes biologically implausible results echoed concerns about cause and effect relationships raised for YTBH models.

Given the diverse model formulations suggested by the parameter prediction approach, *ad hoc* modelling of the three parameters of the combined model was not expected to produce models with superior fit. However, the two approaches explored (using SI or using one or more of slope, aspect and elevation) offered the advantage of effectively constraining the model formulations by *a priori* hypotheses about biological aptness. Resulting models were thus more tenable for practical use and still statistically significant improvements over the base model. The most important hypothesis supported by the analysis was that modelling the *a* coefficient only would represent most differences due to site. The very few cases where modelling both *a* and *b* coefficients produced a statistically significant improvement over the *a* coefficient alone suggested that the shape of the trajectory could also be a function of site quality.

The superior fit of the SI-based *ad hoc* models over other approaches was interesting. In the parameter prediction method, the variables chosen as predictors of each parameter are determined for each parameter independently. However, the three coefficients of the combined model interact closely to determine the shape of the curve. Considered together, the combination is not likely optimal; the reduced set of some combination of slope, aspect and elevation used in *ad hoc* modelling of parameter *a* is not likely optimal either. Thus, the SI-based approach not only offers greater biological aptness, the simpler model is easier to optimize.

Consistent comparisons and recommendations for use of the different models were complicated by the multivariate approach. Many models are poorly extrapolated beyond the range of the data; however, because the matrix of variables sampled was only partially covered, actually identifying the range of data is difficult. Since model behaviour is not easily generalizable, the results of this thesis should be considered preliminary and extended only conceptually beyond the stands from which the data were collected.

The weaknesses identified in this thesis are not unique; modelling efforts are normally enhanced when larger sets of data with greater coverage of the range of conditions under consideration are available. Regardless, statistically significant juvenile height models for both YTBH and height yield beyond breast height were developed using site and stand variables. Moreover, the potential for including site attributes over SI alone and achieving similar precision was demonstrated, especially in the context of qualitative silvicultural interpretations. Further research should overcome problems with extrapolation. Such models would be very useful for crop planning, and at an operational scale would enhance forest management and contribute to the reduction of uncertainty in timber supply.

Despite the weaknesses identified in this thesis, it is unlikely that the information need of the forest manager (*e.g.*, improving precision in estimates of greenup age as they impact timber supply) was efficiently addressed. This is partly because the principal objective of this thesis was constrained to the development of height models, and issues in application of height models in timber supply were outside of the scope of the work.

Therefore, the principal recommendation of this thesis is that a clearly defined framework upon which timber-supply planning issues are addressed be determined. From this framework, attempts to address information deficiencies can be coordinated, so that when large issues are addressed in components, the components efficiently contribute to solving the overall set of management issues.

Several additional recommendations pertain to the particular objectives of this thesis:

- 1. Substantial variability in YTBH exists between stands, and useful models more precise than those based on SI appear possible, given sufficient data and appropriate predictors. Further efforts should be directed to explore this potential.
- 2. Models developed in this thesis can be compared to extant models most sensibly using independent data. Validation data should be obtained from the Nelson region, and the bias and precision of the different models should be compared.
- 3. Representing site quality in height yield models using measures other than SI showed great promise. Models with similar precision appear possible, and would eliminate the need to estimate SI before applying the height model, as is current practice. Further efforts should be directed to explore this potential, using a larger data set, focussed on fewer species to increase efficiency.
- 4. The non-destructive measurement of multiple heights on species with discernable annual growth patterns was generally very effective, and the limitations found in this approach are minimized with practice. The use of this technique should be expanded in future height model data collection.
- 5. The average height approach showed promise, but had greater data needs for a given level of precision when compared to top height. The utility of measures of stand height other than top height should be addressed in management problem analyses, and the potential to implement various approaches discussed with forest biometricians to determine the most efficient options.

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# APPENDIX I – SPECIES CODES, SCIENTIFIC AND COMMON NAMES

Common Name	Species Code	Scientific Name
grand fir	Bg	Abies grandis
sublpine Fir	BI	Abies lasiocarpa
western redcedar	Cw	Thuja plicata
paper birch	Ep	Betula papyrifera
interior Douglas-fir	Fd	Pseduotsuga menziesii var. glauca
western hemlock	Hw	Tsuga heterophylla
western larch	Lw	Larix occidentalis
lodgepole pine	Pl	Pinus contorta var. latifolia
western white pine	Pw	Pinus monticola
interior spruce	Sx	Picea glauca x engelmannii