AN ABSTRACT OF THE THESIS OF

Robert G. Shula for the degree of Master of Science in Forest Science presented on January 26, 1998. Title: Database Development and Application to Characterize Juvenile Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco) and Understory Vegetation in the Oregon and Washington Coast Range Mountains.

Abstract approved: Signature redacted for privacy.

Steven R. Radosevich

The Regional Vegetation Management Model (RVMM) predicts the effects of associated vegetation on the growth and yield of young Douglas-fir (age ≤ 20 years) in the Pacific Northwest, and is a 'front-end' growth model for existing rotation-age growth models. Objectives of this thesis are to: (a) document development of the Coast Range RVMM database, (b) characterize tree and vegetation attributes in the database, (c) describe static tree-level equations used to complete the Coastal RVMM database, and (d) describe a Douglas-fir juvenile-stand height potential index.

Database. Development of the Coastal RVMM database is described with respect to the underlying design matrix, sampling and data collection protocols, extent and location of growth monitoring plots, and attributes of trees (conifer and hardwood) and associated vegetation (herb and shrub). Ninety-eight growth monitoring plots were established in the Coast Range Mountains of Oregon and Washington across a sampling matrix defined by site quality, tree-size and species, and extent and size of associated vegetation.

Static Tree-Level Equations. Development of static tree-level equations to predict tree-level attributes sub-sampled during data collection is described. Equation forms have a basis in biometric literature, although each were uniquely adapted for specific tree performance. Thirty-six prediction equations are described for Douglas-fir, three other conifer species, and six hardwood species

for: single-stem diameter, multi-stem basal area, tree height, crown width, and dbh-d15 relationship. The prediction equations produce unbiased estimates of tree-level attributes with adjusted R^2 values ranging from 0.46 to 0.93.

Juvenile-Stand Height Potential Index. Douglas-fir juvenile-stand height potential index (HPI) was developed using the Coastal RVMM dataset, but augmented with four other datasets to extend database stand age (1 to 36 years breast-height-age) and site quality. The HPI equation is an algebraic-difference formulation of an exponentiated and generalized Schumacher growth equation. In comparison with existing site-index equations: (i) HPI represents greater dominant height growth to about breast-height age 20 years, and (ii) site quality is predicted more consistently across the entire breast-height-age range of the database.

Database Development and Application to Characterize Juvenile Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco) and Understory Vegetation in the Oregon and Washington Coast Range Mountains

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Robert G. Shula

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure Page

LIST OF FIGURES (Continued)

Figure | Page

LIST OF FIGURES (Continued)

Figure Page

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF ABBREVIATIONS

Abbreviation	Description
bh	breast-height (137 centimeters above the ground)
cm	centimeters
CMP	competition measurement plot
CW	crown width
D15	stem diameter at 15 centimeters above the ground
DBH	stem diameter at breast-height (137 cm above the ground)
HPI	height potential index
HT	height
HT-15	height minus 15 centimeters
HT-137	height minus 137 centimeters
m	meters
n	sample size
nstems	number of stems on a multi-stem rootstock

LIST OF ABBREVIATIONS (Continued)

Abbreviation	Description
PMP	PSME (Douglas-fir) measurement plot
pred	predicted
quad	quadrant
R^2	adjusted R-squared (or, coefficient of determination)
RVMM	Regional Vegetation Management Model

Database Development and Application to Characterize Juvenile Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco) and Understory Vegetation in the Oregon and Washington Coast Range Mountains

Chapter 1: Introduction

1.1 Background

From 1987 to 1990, a joint effort of the Oregon State University (OSU) research cooperatives, COPE (Coastal Oregon Productivity Enhancement) and CRAFTS (Coordinated Research on Alternative Forestry Treatments and Systems) was implemented to model the effects of associated vegetation on the growth and yield of young Douglas-fir. Opalach and Radosevich (1988) provide the first published description of this modeling work. Beginning in June 1990, funding for the modeling was continued through a grant from the US Forest Service, Portland, Oregon. The objective of the grant was to develop a Regional Vegetation Management Model (RVMM) to predict young Douglas-fir stand growth and yield (inclusive of associated vegetation competition effects and prescribed vegetation treatments) in Southwest Oregon, and the Coast and Cascade mountains ranges of Oregon and Washington. Shula and Knowe (1991a) describe the status of the modeling effort and a view to the future following the reorganization and redirection of the grant funded project. Goals for the RVMM project in 1991 included: (1) project review and evaluation, (2) expansion of the modeling database using the OSU Department of Forest Science databank, (3) investigation of alternative model forms, (4) investigation of alternative measures of site productivity in young stands, (5) development of a database for long-term growth and yield modeling, and (6) enhancement of the vegetation management decision-support computer program, VEGPRO, (Wagner et al., 1990).

1.2 Objectives

The purpose of this thesis is to document selected portions of the Coast Range RVMM project for which I (i) shared responsibility (development of a database for long-term growth and yield modeling), or (ii) conducted independent research (i.e., investigation of alternative tree-level model forms and the development of a site productivity measure for young Douglas-fir stands).

The specific objectives of this thesis are to:

- document the development of the Coast Range RVMM database,
- statistically characterize tree and vegetation attributes in the database,
- describe the development of static tree-level models, and
- describe the development of Douglas-fir juvenile-stand height potential index to quantify site productivity.

Chapter 2 describes the Coast RVMM database. Descriptions are included of the database matrix and sampling design, data collection protocols, land ownerships and locations, average tree- and stand-level attributes, and visual- and transect-based associated vegetation assessments. The database comprises the empirical basis for the static tree-level equations presented in Chapter 3, and a portion of the empirical basis for the development of the juvenile-stand height potential index presented in Chapter 4.

Chapter 3 describes the development of static tree-level equations which were used to complete the Coastal RVMM database for tree-level attributes sub-sampled during data collection. These equations facilitated a full accounting of per hectare sums and means of relevant stand-level attributes for use in growth analyses.

Chapter 4 describes the development of Douglas-fir juvenile-stand height potential index to quantify site productivity. The database represents 5 independent studies and covers a range in tree breast-height-age from 1 to 36 years. Dominant height is characterized, as is, an algebraic difference approach to model dominant height growth. The base-equation for this approach was determined from a static equation presented in Chapter 3.

Chapter 5 reviews highlights of preceding chapters, recounts the utility of the current work, and suggests potential future work.

Chapter 2: Database

2.1 Background

An important prerequisite for the successful development of the Regional Vegetation Management Model (RVMM) is representative, compatible datasets that provide a database inclusive of tree and associated vegetation competition-effects to model growth and yield at the tree- and stand-level. In 1991, during initial project review and evaluation, existing datasets were found to be deficient, particularly with regard to consistency in measurements of tree and associated vegetation attributes, e.g., diameter and percent cover, respectively. The review is described by Shula and Knowe (1991b), and reports sampling and data collection protocols used by:

- Oregon State University cooperative, Coordinated Research on Alternative Forestry Treatments, CRAFTS (CRAFTS Experimental Design Subcommittee,1981; Walstad and Wagner, 1982; Wagner 1982),
- Oregon State University Forestry Intensified Research (FIR) Program in Southwest Oregon (Tesch et al., 1985), and
- University of Washington cooperative, Stand Management Cooperative, SMC (Maguire, 1990; Newberry, 1985).

The review concluded that, collectively, data collection had not been conducted consistently, systematically, or compatibly across regions, site qualities, and stand ages. Furthermore, usefulness of datasets for biometric analyses of conifers and hardwoods (diameter distribution, stocking, mortality, height-age curves) was limited by the number and selection of tagged trees, and inconsistency in type and method of measurements (e.g., stem diameter, crown width, height to crown base). Dataset interpretation and utility to model tree growth response and vegetation dynamics also was limited by the absence or use of different methods to assess percent cover of vegetation, and the inherent bias against hardwoods evidenced by their exclusion from measurement.

The realization, then, that a sufficient quantity and quality of data was not available spurred:

- establishment of a dataset matrix to guide the overall procurement of new data, and
- establishment of uniform, minimum standards to sample and monitor the growth of individual-trees, forest stands, and associated vegetation.

2.2 Database Matrix

The objective of the database matrix was to guide the acquisition of data to characterize a response surface with regard to site productivity, tree size, tree species and associated vegetation species, competition level, and vegetation management technique. The approach to develop the database matrix was based upon the initial RVMM review and evaluation, previously described (section 2.1). The rationale supporting the formulation of the matrix was to select a limited number of categorical variables which, in practice and in combination, would generate the desired database. Further refinement of the variables defining the database matrix (e.g., specificity to species or vegetation management) was abandoned because the resultant database matrix would grow to an unrealistic size.

2.2.1 The database matrix in-theory

The categorical variables selected to form the database matrix were:

- plant association (Hemstrom and Logan 1986),
- tree height class,

- site preparation treatment, and
- competition release of conifers.

These categorical variables were considered basic building blocks to deliver the desired response surface with regard to site productivity (plant association), tree size (height class), competition level and vegetation management (site preparation and competition release of conifers). A representative range in tree species (conifer and hardwood) and associated herb and shrub species were to be sampled within a matrix cell by conscious effort during fieldwork (reconnaissance and plot installation). Replication within these categorical variables was included to sample natural variation expressed in the data.

Plant Association. The use of plant association as a class variable allowed a distribution of plots across a site productivity gradient from most to least productive (Means and Sabin, 1989). For the Oregon and Washington Coast Range Mountains, the plant associations described by Hemstrom and Logan (1986) were used. Plant associations represent major groupings of indicator tree species correlated with measures of site productivity (e.g., site index, Hann, 1995). Furthermore, when crossed with the class variables, `site preparation' and `conifer release', a variety of associated tree and vegetation species of interest would be represented in the database. For example, a conscious effort was made to include:

- conifer species: Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), Sitka spruce (*Picea sitchensis* [Bong.] Carr.);
- hardwood species: red alder (*Alnus rubra* Bong.), vine maple (*Acer circinatum* Pursh.), cherry (*Prunus emarginata* [Doug.] Walp.), hazel (*Corylus comuta* Marsh.), cascara (*Rhamnus purshiana* DC.), chinquapin (*Castanopsis chrysophyla* [Doug.] DC.), bigleaf maple (*Acer macrophyllum* Pursh.), willow (*Salix* spp.);

- herbaceous species: bracken fern (*Pteridium aquilinum* [L.] Kuhn.), swordfern (*Polystichum munitum* Kaulf.), willow-herb (*Epilobium* spp. L.), thistle (*Cirsium* spp. L); and,
- shrub species: Oregon grape (*Berberis nervosa* Pursh.), Salmonberry (*Rubus spectabilis* Pursh.), salal (*Gaultheria shallon* Pursh.), rhododendron (*Rhododendron macrophyllum* G. Don). huckleberry (*Vaccinium* spp. L.), buckthorn (*Ceanothus* spp. L.).

In the database, species were identified by the appropriate Garrison code (Garrison and Skovlin, 1976) which is comprised of the first two letters of the Latin genus name and the first two letters of the Latin species name. For example, Douglas-fir is represented by 'PSME'. Appendix 1 provides a list of species and Garrison codes cited in this thesis. Plant associations that represented high, medium, and low site productivity were selected and included: (a) TSHE / RUSP / ACCI, (b) TSHE / POMU, and (c) TSHE / GASH, respectively (Hemstrom and Logan, 1986).

Tree Height Class. Mean stand tree (Douglas-fir) height was used as an explicit class variable of tree size, and as a surrogate for stand age. Ultimately, there was the expectation that the RVMM would 'handoff' to rotation-age models (e.g., ORGANON, Hann et al., 1995) on the basis of attained tree size, not age. Nonetheless, in the database matrix, the stand age accompanying a given height class was documented. Height classes to mean tree height 7.5 meters, provided tree size specificity (height, diameter, crown size) in relation to various levels of inter- and/or intraspecific competition. Height classes greater than 7.5-meters through mean tree height 13.5 meters, provided tree size specificity at the upper-end of the tree size modeling domain.

Site Preparation Treatment. Pre-planting site preparation treatment was included as a categorical matrix variable due to the variety and abundance of associated vegetation thought to be influenced by the presence or absence of treatment. In practice, the site preparation matrix variable was either a 'yes' or 'no' with respect to whether the treatment was performed or not performed on potential sites for inclusion in the database. Site preparation treatments included burning and/or herbicide spraying, but also mechanical scarification. The robustness of this matrix element was to be augmented when crossed with the matrix variable `conifer release'. The ability to fill these matrix cells in the two upper height classes was dubious, given the high prevalence of site preparation (burning) over the previous 20 years.

Competition Release of Conifers. Competition release of conifers (hereafter, conifer release) from associated vegetation and/or other conifer and hardwood trees (i.e., precommercial thinning) was an important element to include in the competition-modeling database matrix. In practice, the conifer release matrix variable was either a 'yes' or 'no' with respect to whether the treatment was performed or not performed on potential sites for inclusion in the database. Conifer release from associated vegetation included a range of chemical and manual treatments. The representation of associated species and competition levels was broadened with the crossing of 'conifer release' with the class variables `site preparation' and 'replication'.

Table 1 presents the database matrix in abbreviated form. It was decided that, given time and money constraints, all combinations of matrix variables (cells) would not be filled. Thus, fieldwork would focus on filling portions of the matrix most critical to provide the aforementioned response surface.

Table 1. Database Matrix to Guide the Acquisition of Data for the RVMM.

Number of Plant Associations[1]	Number of Tree Height Classes[2]	Number of Site Preparation, Competition Release Classes[3]	Number of Replications	Total Number of Cells per Region
3	7	8	3	504

1. (a) TSHE/RUSP/ACCI (high productivity plant association)
   (b) TSHE/POMU (medium productivity plant association)
   (c) TSHE/GASH (low productivity plant association)
2. height classes 0 to 7.5 meters in five - 1.5 meter classes, and 7.5 to 13.5 meters in two - 3.0 meter height classes.
3. 'yes' and 'no' permutations for the occurrence of site preparation, conifer release, and precommercial thinning treatments.

The database matrix established a potential of 504 permanent plots per region. The 3 regions of interest included: the Oregon and Washington Coast Range Mountains, Southwest Oregon, and the Oregon and Washington Cascades Mountains (west-side).

2.2.2 The database matrix in practice.

While the database matrix defined a potential of 504 permanent plots, in practice the final Coastal RVMM sampling included 98 permanent plots. As described below, these plots included portions of the matrix deemed most critical to provide the desired response surface with regard to plant association; height class; and, site preparation and conifer release. Replication within a cell ranged from 1 to 6, but was predominantly 2.

Plant Association. Plots were installed across plant associations (high, medium, and low site productivity), although representation is weighted toward high site productivity (Table 2). Priority was not given to high site productivity stands, rather, these were the stands most often identified by landowners for potential plot installation. Difficulty in locating acceptable medium and low site productivity stands, resulted in a greater number of the high site productivity stands being selected for plot installation. In practice, landowners provided potential stands for plot installation based upon their definition of site productivity, e.g., plant association or site-index. No attempt was made to interchange plant association and site index once a stand had been assigned by a landowner.

Table 2. Number of Coast Range RVMM Permanent Plots by Landowner and Site Productivity.

Landowner	Site Productivity			Total
	High	Medium	Low	
USDA Bureau of Land Management	3		1	4
Boise Cascade Corporation	1	4	3	8
Champion International	2			2
International Paper Compay	8	3	1	12
Rayonier		10		10
Lone Rock Timber Company	4			4
Oregon Department of Forestry			3	3
USFS PNW Station	19		4	23
Simpson Timber Company	4	3	4	11
Starker Forests	4	2	1	7
Weyerhaeuser Company	1	5	2	8
Willlamette Industries		2	4	6
Total	46	29	23	98

Tree Height Class. Height classes most critical to fill included: 0-1.5, 1.5-3, 3-4.5, 6-7.5, and 10.5-13.5 meters (Table 3) because these height classes concentrated effort in younger trees (the focus of RVMM), while they also included the full range of tree size within the domain of the entire modeling effort. Height class 4.5-6 meters was considered lower priority; however, difficulty in locating acceptable 3-4.5 meter class stands, resulted in a greater number of the 4.5-6 meter class being filled.

Table 3. Number of Coast Range RVMM Permanent Plots by Height Class and Site Productivity Class.

Height Class (meters)	Number of Plots by Site Productivity Class			Total
	High	Medium	Low	
0 - 1.5	5	6	6	17
1.5 - 3.0	6	6	5	17
3.0 - 4.5	2	2	1	5
4.5 - 6.0	4	4	4	12
6.0 - 7.5	2	3	2	7
7.5 - 10.5	18	8	5	31
10.5 - 13.5	9			9
Total	46	29	23	98

Site Preparation Treatment and Conifer Release. Matrix cells most critical to fill included the following 'yes', 'no' permutations for site preparation treatment, conifer release from associated vegetation, and precommercial thin: n/n/n, y/n/n, and y/y/n, respectively (Table 4). These categories prioritized the selection of younger stands prior to the advent of intra-specific competition, while they also provided the range of stand management from none to intensive.

Table 4. Number of Coast Range RVMM Permanent Plots by Height Class and the Stand Treatments: Site Preparation, Conifer Release, Precommercial Thin.

Height Class (meters)	'Yes' and 'No' Permutations for the Occurrence of the Treatments: Site Preparation / Conifer Release / Precommercial Thin								TOTAL
	n/n/n	y/n/n	n/y/n	y/y/n	n/n/y	y/n/y	n/y/y	y/y/y	
0 - 1.5	5	5	1	6					17
1.5 - 3.0	5	7	1	4					17
3.0 - 4.5	1	3		1					5
4.5 - 6.0	3	5		4					12
6.0 - 7.5	1	2		4					7
7.5 - 10.5	5	8	2	11		2	1	2	31
10.5 - 13.5	1	1		2	1	2		2	9
TOTAL	21	31	4	32	1	4	1	4	98

2.3 Plot Design and Establishment

The premise of the plot design was that both tree- (e.g., diameter-at-breast-height) and stand-level (e.g., basal area per hectare) descriptions of tree and associated vegetation (percent cover) should be represented. This meant that bounded plots were necessary for a representative sample of trees (conifer and hardwood species) and associated vegetation.

The sampling scheme comprised two types of plots (Figure 1):

- PSME Measurement Plot (PMP): one, rectangular 0.04-hectare plot (20 meters by 20 meters) located parallel to planting rows with actual plot size influenced by the inclusion of about 50 Douglas-fir crop trees;

- Competition Measurement Plot (CMP): four, circular 0.004-hectare plots (3.6 meters in diameter), nested within a PMP; located on a uniform grid (not tree-centered), and divided into quadrants, with each quadrant containing a centrally located vegetation line transect (2 meters in length).

PMPs provided stand-level data on trees (conifers and hardwoods), while CMPs provided data on associated vegetation in relation to trees in the 'neighborhood' (either full CMP, individual quadrants, or on-average across all CMPs). Data at the CMP level, therefore, would be useful for both stand- and tree-level inter- and intra-specific competition analyses. CMP vegetation assessment included both visual (subjective) and line-transect (less subjective) methods (see section 2.4) to investigate the potential of each method to characterize associated vegetation.

PMPs were subjectively established within stands in accordance with the specifications of the database matrix. Furthermore, stands were accepted if tree stocking was reasonably uniform and adequate (≥ 494 trees per hectare, tph), slope and slope position were uniform, and animal damage was minimal. PMPs were located with plastic pipe at one plot corner (usually the NE corner) with a tag giving PMP number, plot dimensions, and azimuth along two perpendicular sides. PMP location was referenced from the nearest road with another plastic pipe.

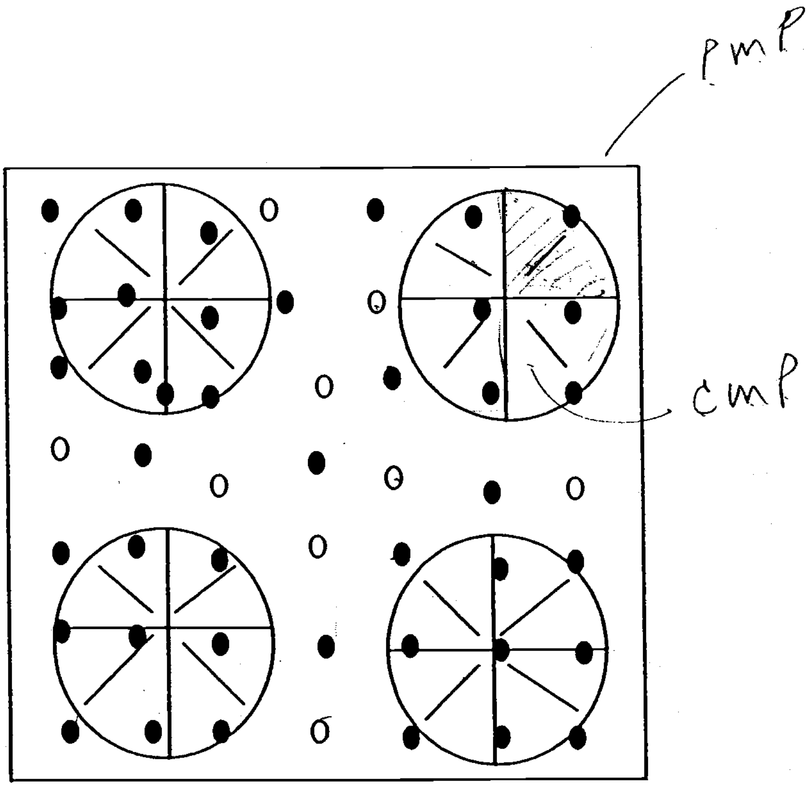

Figure 1. Sampling scheme: one 0.04-ha PMP (20m x 20m) with 4 nested 0.004-ha CMPs (3.6 m diameter) with vegetation line transects (2 m) located within each quadrant. Dots: intensively measured trees (filled) and basic measurement trees (unfilled) (Tables 5 and 6).

The PMP boundaries were flagged approximately every 3 meters; plot corners were double flagged. CMPs were located on a uniform grid with a plastic pipe at plot center. Quadrants were flagged at the four cardinal directions. Sample trees were tagged with write-on tags, and stem diameter measurement locations (diameter at 15 cm above the ground, d15; and/or diameter-at-breast-height, 137 centimeters, dbh) were marked with tree paint. In the case of multiple-stems, the largest diameter stem was tagged, while subsequent stems (up to five total stems) were marked with the respective number of paint marks. Vegetation transects were located in the center of each CMP quadrant center (NE, SE, SW, or NW) with each transect end pin-flagged.

2.4 Tree and Vegetation Measurement Protocols

Measurement protocols established minimum standards for data acquisition and integrity to support the tree- and stand-level growth and yield models. Tables 5 and 6, respectively, present the assessment rules and attribute measurements.

Table 5. Assessment Rules for Data Acquisition.

Vegetation	Assessment Rule
Conifers	Basic attributes on all trees ≥ 15 cm tall on the PMP Additional intensive attributes on all trees ≥15 cm tall on CMPs and on sub-sample of trees across size range on the PMP
Hardwoods	Basic attributes on all hardwood rootstocks (single- or multi-stem) on the CMP Additional intensive attributes on 4 hardwood rootstocks per CMP across size range (comprising 1 small, 2 average, and 1 large)
Associated Vegetation	Percent cover and average total height by CMP quadrant regardless of presence or absence of trees

Table 6. Basic and Additional Intensive Attribute Measurements.

Vegetation	Basic Attribute	Additional Intensive Attribute
Conifers	PMP, CMP, quadrant number Species code • Garrison and Skovlin (1976) Tree number Diameter (at 15 cm, d15; and/or 1.37 m, dbh) • d15: ht < breast-height • d15 and dbh: ht ≤ 3 m • dbh: ht > breast-height Condition code	Crown width • 2 directions, 90 degrees pivot Height to crown base • 3/4 around live Total height
Single-stem hard-woods	PMP, CMP, quadrant number Species code • Garrison and Skovlin (1976) Diameter • dbh: ht > breast-height Total height • ht < 3 m Crown width • ht < 3 m • 2 directions, 90 degrees pivot Condition code	Tree number Diameter • d15: ht < breast-height • d15 and dbh: ht ≤ 3 m • dbh: ht > breast-height Crown width • 2 directions, 90 degrees pivot Height to crown base • 3/4 around live Total height
Multi-stem hard-woods	PMP, CMP, quadrant number Species code • Garrison and Skovlin (1976) Number of stems per rootstock Diameter (up to 5 largest stems per rootstock) • dbh: ht > breast-height average total height of clump • ht < 3 m crown width of clump • if ht < 3 m • 2 directions, 90 degrees opposite Condition code	Rootstock number Stem number • up to 5 largest stems Diameter • d15: ht < breast-height • d15 and dbh: ht ≤ 3 m • dbh: ht > breast-height Height to crown base • rootstock average Total height • rootstock average

Table 6, Continued. Basic and Additional Intensive Attribute Measurements.

Vegetation	Basic Attribute	Additional Intensive Attribute
Herbs (including organic material & bare ground) Shrubs	PMP, CMP, quadrant number Species code • Garrison and Skovlin (1976) Percent cover • visual estimate by quadrant Average total height • visual estimate by quadrant	Covered length on transect by quadrant • measured with meter stick Average total height • visual estimate by quadrant

On the PMP, all conifers were sampled for the basic attributes, diameter and condition; but, were sub-sampled (about 30% of the total number of trees on the PMP) for additional intensive attributes, total height, crown width, and height-to-crown-base (height to branch whorl with 3/4-around live branches) (Table 6). On the CMP, all conifers were sampled for basic and additional intensive attributes, while all hardwoods were sampled for basic attributes, but sub-sampled (four rootstocks per CMP across the size range: 1 small, 2 medium, 1 large) for additional intensive attributes (Table 6). Associated vegetation on the CMP was assessed by quadrant as percent cover (0 to 100%) at each of two vegetation layers, herbaceous (herbs, organic material, bare ground) and shrub using visual and line transect methods (section 2.7). The visual assessment provided estimates of percent cover directly, while the line transect assessment provided estimates of percent cover indirectly via transformation (i.e., the covered length along a 2-meter line transect) (section 2.7).

2.5 Land Ownership and Plot Locations

PMPs were established over a wide variety of land ownerships (Table 2) and geographic locations. Land ownership included 9 private companies and 3 public agencies. Geographic locations included the west-side Coast Range Mountains of Oregon and Washington (from near Forks, Washington to near Coos Bay, Oregon), while east-side Coastal Range locations ranged from near Shelton, Washington to near Roseburg, Oregon.

2.6 Stand- and Tree-Level Attributes

Mean stand-level attributes of tree size and stocking density on PMPs were determined using the SAS (SAS Institute Inc.1989) statistical procedure, MEANS. Tables 7 and 8, respectively, present descriptive statistics as mean stand-level attributes of tree size and stocking density on PMPs with stocking < breast-height and stocking > breast-height in the Coast Range RVMM database. This separate presentation is provided to accent these two strata of stand structure. Table values are based on both conifer and hardwood trees occurring on the PMPs. Trees included in the calculation of PMP means were healthy, planted Douglas-fir and healthy hardwoods.

'Rootstocks per hectare' (Table 7 and 8) refers to entire individual plants, and refers to both single- and multi-stemmed trees with respect to tree stocking per unit-area. 'Basal area per hectare' is a unit of measurement (Clutter et al., 1983) that represents the sum-total of stem cross-sectional area based on either d15 or dbh. Quadratic mean diameter is stem diameter (at either 15 cm or 137 cm above the ground) that corresponds to a tree of mean basal area in a stand (Clutter et al., 1983). Geometric crown width is a measure of tree crown-size (Clutter et al., 1983), and is calculated as the square-root of the product of crown width (diameter) measured in two perpendicular directions (Table 6).

Table 7. Mean (n=55 PMPs) Attributes for Stocking < Breast-Height.

Attribute	Mean (standard error)	Minimum	Maximum
Plantation age (years)	7.4 (0.6)	1.0	15.7
No. rootstocks per hectare	1274 (400)	12	21250
Basal area (m^2/hectare) at 15 cm	0.164 (0.026)	0.001	0.998
Quadratic mean diameter (mm) at 15 cm above the ground	15.4 (1.0)	3	39
Total height (cm)	84.4 (3.6)	25	136
Geometric crown width (cm)	44.7 (2.4)	8	91

Table 8. Mean (n=94 PMPs) Attributes for Stocking > Breast-Height.

Attribute	Mean (standard error)	Minimum	Maximum
Plantation age (years)	10.2 (0.4)	1.0	16.0
No. rootstocks per hectare	1513 (112)	62	6174
Basal area (m^2/hectare) at 137 cm	9.59 (0.91)	0.00	30.11
Quadratic mean diameter (mm) at 137 cm above the ground	79.7 (5.7)	7	211
Total height (cm)	588.5 (33.7)	153	1306
Geometric crown width (cm)	269.0 (13.5)	63	556

Figures 2a and 2b and 2c and 2d illustrate the range in tree size (total height, geometric crown width, stem diameter) represented in the Coast Range RVMM database for PMPs with stocking < breast-height and stocking > breast-height for Douglas-fir and hardwoods, respectively.

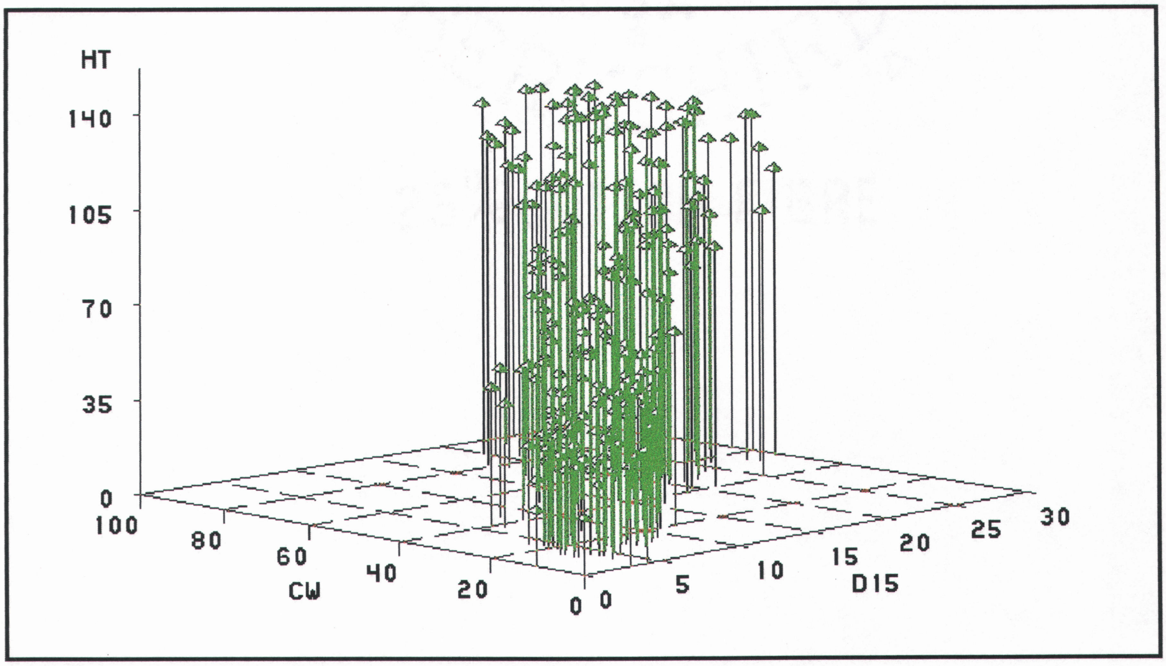

Figure 2a. Individual Douglas-fir trees less than breast-height in the Coastal RVMM database (n = 310); characterised by total height (HT, cm), geometric crown width (CW, cm), stem diameter at 15 cm above the ground (D15, mm).

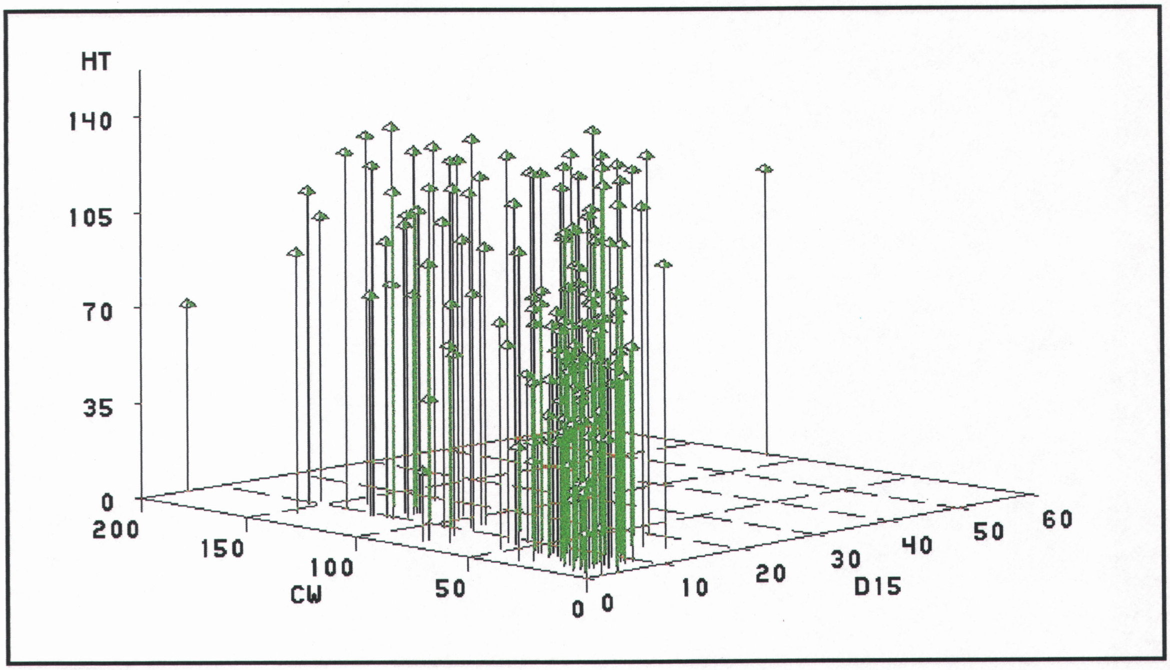

Figure 2b. Individual hardwood trees less than breast-height tall in the Coastal RVMM database (n = 253); characterised by total height (HT, cm), geometric crown width (CW, cm), stem diameter at 15 cm above the ground (D15, mm).

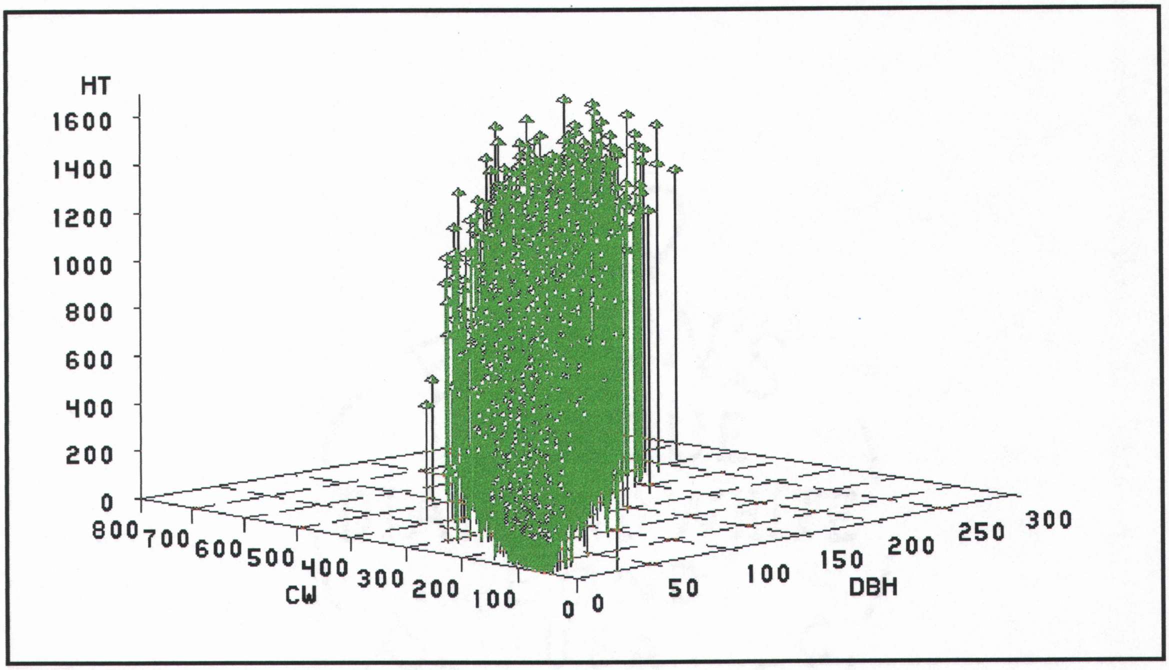

Figure 2c. Individual Douglas-fir trees above breast-height in the Coastal RVMM database (n = 2148); characterised by total height (HT, cm), geometric crown width (CW, cm), stem diameter at 137 cm above the ground (DBH, mm).

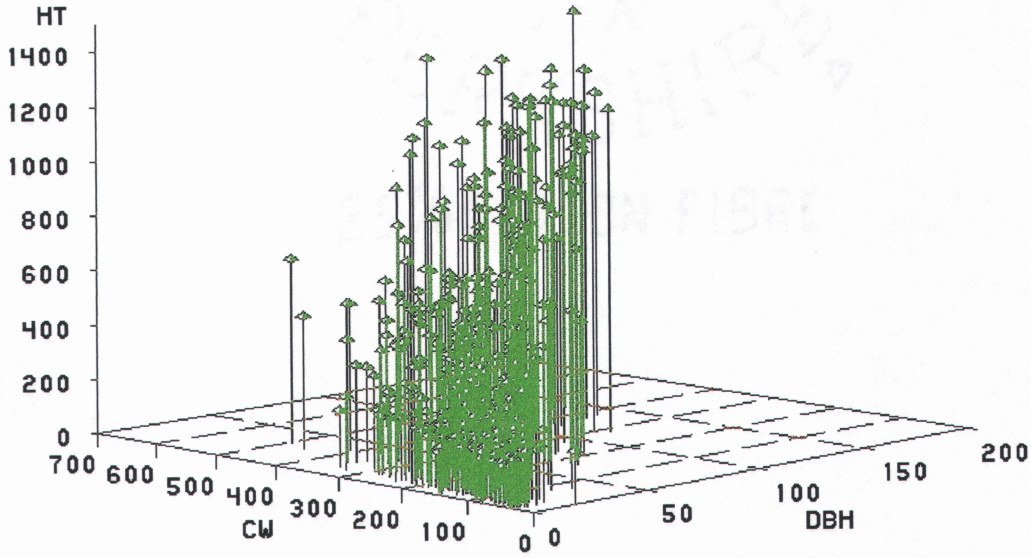

Figure 2d. Individual hardwood trees above breast-height in the Coastal RVMM database (n = 432); characterised by total height (HT, cm), geometric crown width (CW, cm), stem diameter at 137 cm above the ground (DBH, mm).

2.7 Vegetation: Visual- and Transect-Based Assessments

The comparison of central tendency statistics (mean, minimum, maximum, coefficient of variation) for visual- and transect-based vegetation assessments in the RVMM Coast Range database were possible at several levels of resolution, e.g., the individual quadrants (n=1568), the CMPs (n=392, each a mean of 4 quadrants), and the PMPs (n=98, each a mean of 16 quadrants). Across these levels of resolution, mean values were identical, however, dispersion statistics (e.g., variance) about the means differed due to the different intensities of data reduction.

Tables 9 and 10 provide measures of central tendencies (mean, minimum, maximum, coefficient of variation) at the individual quadrant and PMP levels of resolution for visual- and transect-based assessments of percent cover and height of vegetation, respectively. Tables 11 and 12 provide similar statistical information, but with respect to the deviation between transect- and visual-based assessments (transect minus visual) for percent cover and height of the vegetation.

Table 9. Mean, Minimum, Maximum, and Coefficient of Variation for Visual- and Transect-based Percent Cover Assessment at the Individual Quadrant (Quad) (n=1568) and PMP (n=98) Level.

Vegetation		Mean % Cover (Quad / PMP)	Minimum % Cover Maximum % Cover		Coefficient of Variation (%)	
			Quad	PMP	Quad	PMP
Herb	Visual	21	0 100	0 88	120	102
	Transect	22	0 100	0 95	123	96
Shrub	Visual	34	0 100	0 97	91	72
	Transect	36	0 100	0 97	95	71
Organic Material	Visual	74	0 100	11 100	37	31
	Transect	74	0 100	5 100	40	31
Bare Ground	Visual	4	0 85	0 46	294	211
	Transect	4	0 93	0 48	359	231

Table 10. Mean, Minimum, Maximum, and Coefficient of Variation for Visual- and Transect-based Height Assessment at the Individual Quadrant (Quad) (n=1568) and PMP (n=98) Level.

Vegetation		Mean Height (cm)		Minimum Height Maximum Height (cm)		Coefficient of Variation (%)	
		Quad	PMP	Quad	PMP	Quad	PMP
Herb	Visual	50		0 400	0 215	106	83
	Transect	39		0 300	0 224	127	97
Shrub	Visual	95		0 700	0 338	116	96
	Transect	77		0 642	0 325	140	110

Table 9 reveals that mean percent cover is nearly the same for the two methods of vegetation assessment, visual and transect. The transect method provides slightly greater values of herb and shrub percent cover, but slightly reduced values for organic material and bare ground. Minimum, maximum and coefficient of variation (c.v.%) values for percent cover indicate that variation is less pronounced (reduced range and c.v.%) at the PMP level of resolution (n=98) probably due to the greater level of data reduction. At the quadrant level of resolution, the transect method exhibits a greater degree of variability (greater c.v.%) than the visual method probably because the observer can discriminate better in allocating species coverage along the transect, than visually across an entire quadrant. This degree of variability is reduced at the PMP level of resolution, again, probably attributed to the greater level of data reduction.

Table 10 reveals that the two methods of vegetation assessment consistently differ (visual greater than transect) in the estimation of mean height of herbs and shrubs. Observations made in the field suggest that the transect method often underestimates total height of vegetation because the measurement is restricted to the portion of a plant directly above the transect which does not necessarily coincide with the total height of the plant.

Table 11. Mean, Minimum, Maximum, and Coefficient of Variation for Visual- and Transect-based Percent Cover Deviations (Transect minus Visual) at the Individual Quadrant (Quad) (n=1568) and PMP (n=98) Level.

Vegetation	Mean Deviation (% Cover)		Minimum Deviation Maximum Deviation (% Cover)		Coefficient of Variation (%)	
	Quad	PMP	Quad	PMP	Quad	PMP
Herb	0.86		-80 85	1 16	1994	46
Shrub	2.14		-90 80	-18 29	927	923
Organic Material	-0.36		-85 80	-17 33	-5246	376
Bare Ground	-0.35		-70 83	-29 24	-2654	-2405

Table 12. Mean, Minimum, Maximum, and Coefficient of Variation for Visual- and Transect-based Height Deviations at the Individual Quadrant (Quad) (n=1568) and PMP Level (n=98).

Vegetation	Mean Height Deviation (cm)		Minimum Deviation Maximum Deviation (cm)		Coefficient of Variation (%)	
	Quad	PMP	Quad	PMP	Quad	PMP
Herb	-11.45		-400 250	-81 18	-324	-1185
Shrub	-18.24		-700 357	-124 57	-395	-120

Tables 11 and 12 provide deviations (transect minus visual) in mean percent cover and height indirectly referenced in Tables 9 and 10 for herbs, shrubs, organic material, and bare ground. Minimum and maximum values, and coefficients of variation on the quadrant and PMP reveal the high degree of variability that is obscured through data reduction.

Figures 3a and 3b, and 4a and 4b illustrate deviations at the quadrant level (n=1568) for percent cover of herb and shrub, and height of herb and shrub, respectively. The figures illustrate that the two methods of vegetation assessment, transect and visual, are most similar with respect to percent cover when percent cover is near 50%; while with respect to vegetation height, the methods steadily diverge as height increases.

Figures 5a and 5b, and 6a and 6b provide similar illustrations, but at the PMP level (n=98); and, demonstrate the reduction in variation between methods that occurs through data reduction (mean-level data).

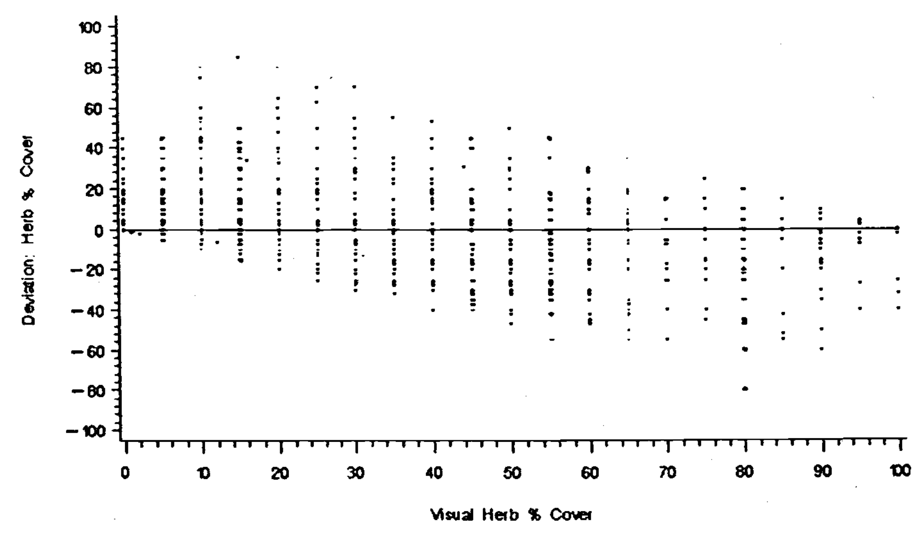

Figure 3a. Deviations (transect minus visual percent cover of herb) by visual percent cover of herb at the quadrant level (n=1568).

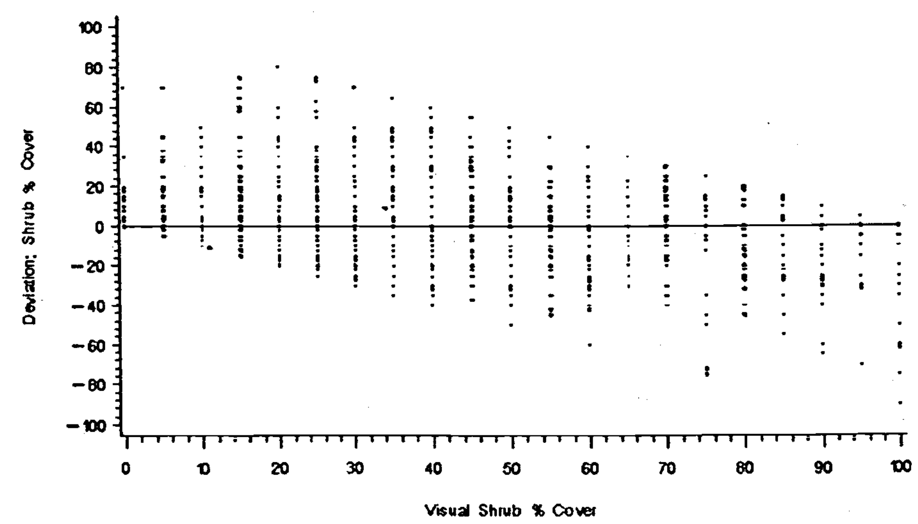

Figure 3b. Deviations (transect minus visual percent cover of shrub) by visual percent cover of shrub at the quadrant level (n=1568).

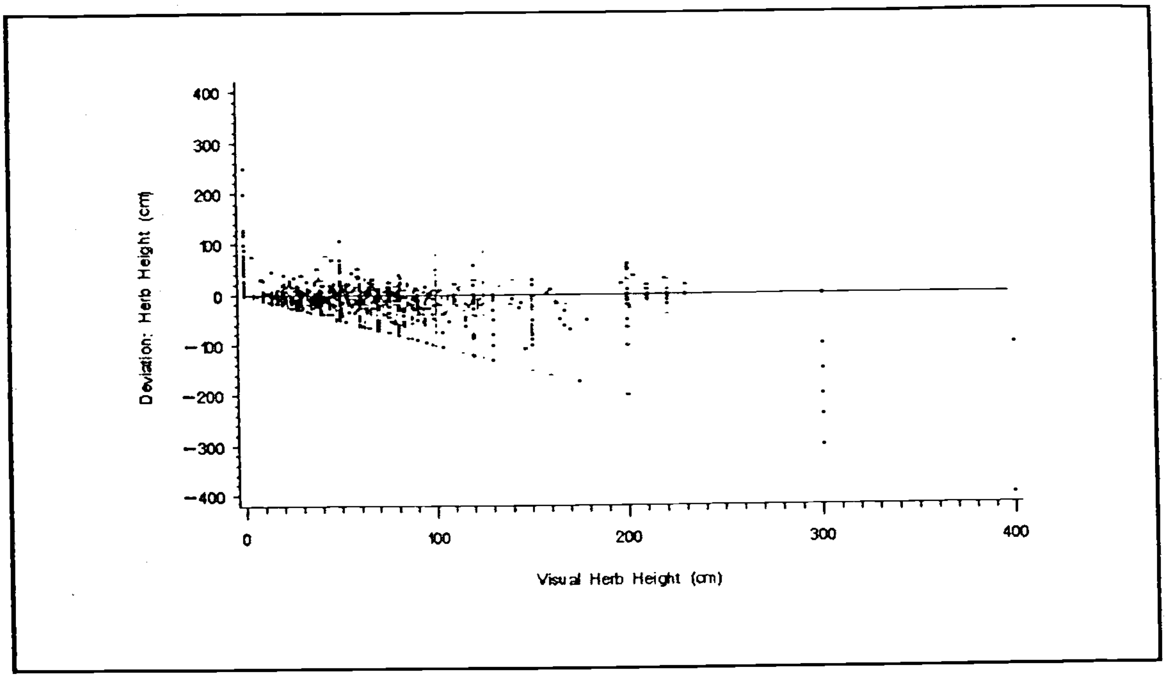

Figure 4a. Deviations (transect minus visual height of herb) by visual height of herb at the quadrant level (n=1568).

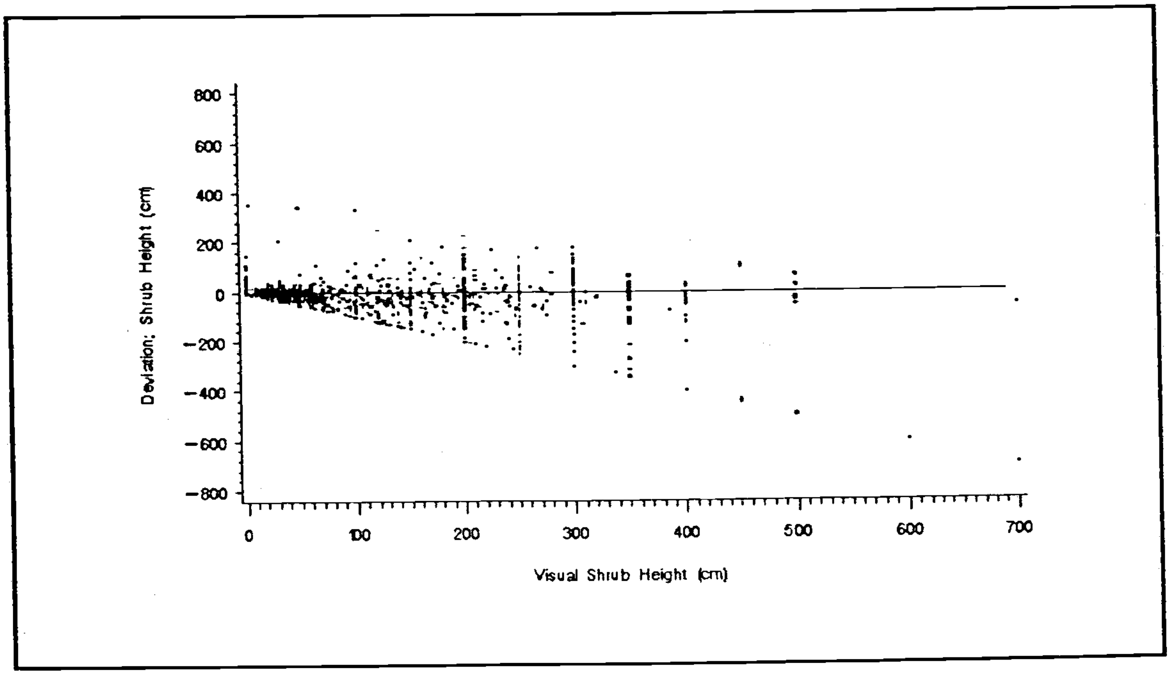

Figure 4b. Deviations (transect minus visual height of shrub) by visual height of shrub at the quadrant level (n=1568).

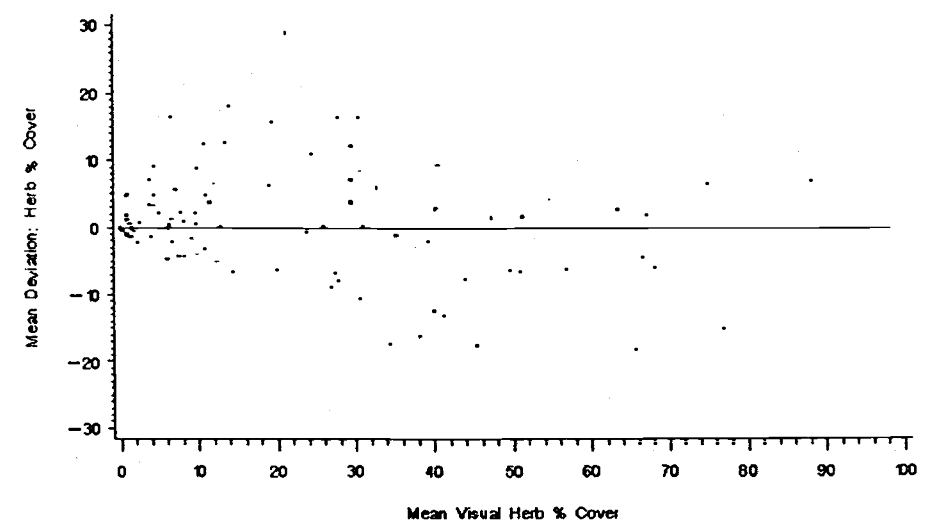

Figure 5a. Deviations (transect minus visual percent cover of herb) by visual percent cover of herb at the PMP level (n=98).

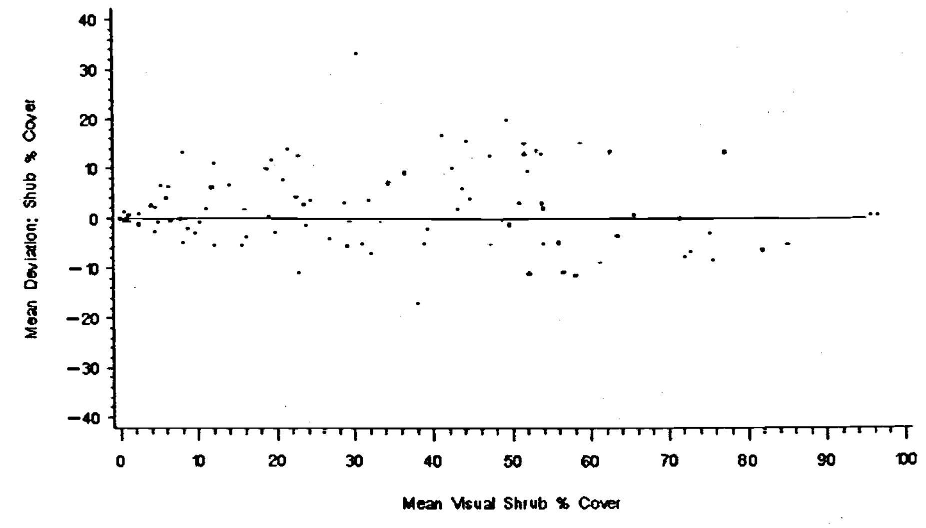

Figure 5b. Deviations (transect minus visual percent cover of shrub) by visual percent cover of shrub at the PMP level (n=98).

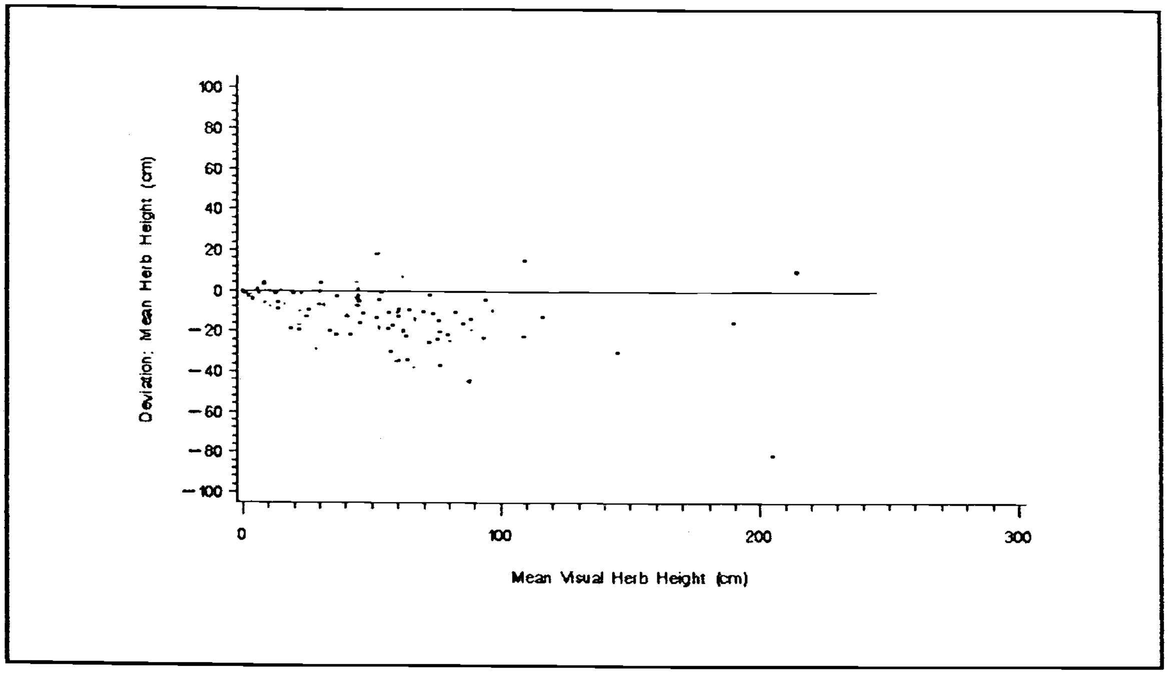

Figure 6a. Deviations (transect minus visual height of herb) by visual height of herb at the PMP level (n=98).

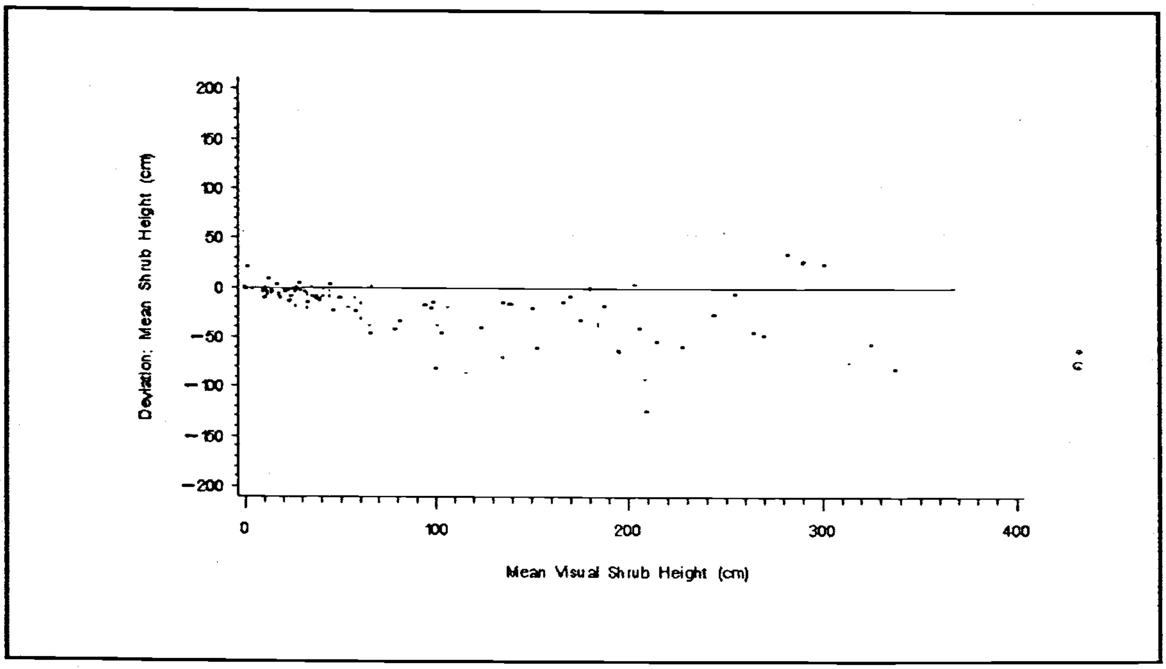

Figure 6b. Deviations (transect minus visual height of shrub) by visual height of shrub at the PMP level (n=98).

2.8 Discussion

The database matrix provided a good template to establish PMPs across a response surface defined by site; tree species; vegetation species; and stand management. However, there was an inclination to establish PMPs on high site quality forest land (Table 2) and in stands with a mean tree height of 7.5 to 10.5 meters (Table 3). Since Coastal RVMM is to be a 'young' stand model, in retrospect, more attention should have been given to stands ≤ 6 meters tall. For example, height class 3.0 to 4.5 meters and 7.5 to 10.5 meters are particularly under- and over-represented, respectively. Nonetheless, there still existed adequate data for the development of the RVMM to predict young Douglas-fir stand growth and yield (inclusive of associated vegetation competition effects and prescribed vegetation treatments).

Plot design (PMPs with nested CMPs) provided an excellent opportunity to collect tree and associated vegetation at the stand- and tree- level. Plot establishment and re-measurement proceeded smoothly taking on average 1.0 and 0.5 days, respectively, with a 3-person crew. Plot integrity (boundary flags, plastic plot-corner posts, tree tags, line transect pin-flags) of the PMP and CMPs remained intact over the 2 year remeasure period. This means that this semi-permanent method of plot establish is acceptable and recommended for growth monitoring of trees and associated vegetation in young stands.

Tree and vegetation measurement protocols were acceptable, although the lower sampling intensity of hardwoods versus conifers (0.02-hectare versus 0.04-hectare, respectively) unbalanced the sample size of conifers and hardwoods (Figures 2a, 2b, 2c, 2d). Nonetheless, it is expected that time and budget constraints would limit the ability of any effort to sample hardwoods as intensively as conifers. This is because the propensity for hardwoods to produce multi-stem rootstocks inflates plot establishment and measurement time by at least a factor of two.

Stand- and tree-level attributes were obtained for planted Douglas-fir and all hardwood stocking < breast-height and stocking > breast-height on 56% and 96% of the PMPs, respectively (Tables 7 and 8). While the filled matrix shows an under-representation of stands with mean height 3.0 to 4.5 meters (Table 3), on a tree-level basis, there is a smooth and continuous distribution of tree sizes by height, geometric crown width, and stem diameter (Figures 2a, 2b, 2c, 2d). These data, then, provide a solid database to predict young Douglas-fir stand growth and yield, inclusive of associated vegetation competition effects and prescribed vegetation treatments.

Visual- and line transect-based vegetation assessments were obtained at the individual quadrant level, or on-average at the CMP or PMP level to characterize vegetation and permit the quantification of stand (tree and associated vegetation) growth dynamics. On-average, the assessment of percent cover was independent of the method of assessment, although variability was affected (Tables 9 and 11, and Figures 3a and 3b). At the quadrant level, the visual method was less variable than the transect method (Table 9). Therefore, the visual method is more likely to be useful to predict vegetation dynamics at that level of resolution because variance has been homogenized. At the PMP level, the transect method was less variable than the visual method (Table 9). Therefore, the transect method is more likely to be useful to predict vegetation dynamics at that level of resolution (again, because variance has been homogenized). On average, the assessment of vegetation height was dependent on the method of assessment (Table 10) with the line transect-based method consistently under-estimating plant height (Tables 10 and 12, and Figures 4a and 4b). Therefore, the visual method of height assessment is recommended.

Chapter 3: Static Tree-Level Equations

3.1 Background

A static tree-level measurement that is commonly sampled in forestry is total tree height (Wang and Hann 1988). The term 'static ' is used to denote a point-in-time tree-level attribute, and to avoid confusion with a 'dynamic' growth-through-time tree-level attribute (e.g. dbh periodic annual increment). Sampling is used in fieldwork because it is logistically impractical to measure every tree for all attributes (e.g., diameter, height, crown-width). Accordingly, in the RVMM database, a number of intensive, sampled tree-level attributes needed to be estimated (Chapter 2, Tables 5 and 6) to complete the database and to facilitate a full accounting of per hectare sums and means of all relevant stand-level attributes (e.g., basal area, quadratic mean diameter, mean height, stem volume). Although individual-stem diameter is an important attribute to predict, the propensity of hardwoods to produce multiple stems also requires the prediction of either (a) diameter of individual stems of a clump, or (b) entire clump basal area. Because height and crown width of multi-stem hardwoods were measured with respect to an entire rootstock (Table 6, Chapter 2), static tree-level equations were developed to predict multi-stem (clump) basal area, rather than the number-of and diameters-of the stems comprising a clump.

A tree-level diameter association that is important to have in the RVMM is the relationship between stem diameter at d15 (diameter at 15 cm above the root collar) and dbh (diameter at breast-height, or 1.37 meters). While both tree diameters are not required on every tree in the database, establishing the diameter relationship does fulfill a growth modeling requirement to move the focus of stem diameter from d15 to dbh as trees grow through and above breast-height (bh). During data collection, this transfer of diameter datum-point is made to increase measurement convenience and precision. In a growth model, the switch from d15 to dbh requires a static equation to predict dbh as a function of some other tree-size attribute (e.g., total height, d15, crown width). In the development of the RVMM database, data to develop a dbh-d15 relationship was collected via the already established protocol (Table 6, Chapter 2) which entails measurement of both d15 and dbh for trees with $15 <$ total height ≤ 300 cm.

The focus of this Chapter is restricted to static tree-level equations developed for a select number of important tree species. Selection was guided by the need to demonstrate both form and utility of the equations across a range of tree species.

3.2 Methods

3.2.1 General

Non-linear estimation procedures (SAS Institute Inc. 1989) were used to determine the parameter coefficients of the static tree-level equations. An alpha (α) level of 0.05 was used to denote the significance of parameter coefficients, although in some cases, parameters of lesser statistical significance were left in the final equation. Most often these parameters remained in equations to improve predictability of a dependent variable for which sample size was limited and variation extreme. Criteria for judging equation goodness-of-fit included adjusted R^2 (Kmenta 1986) and Furnival's Index (Furnival 1961).

Adjusted R^2 value was used because it considers the number of explanatory variables (p) in an equation in relation to the number of observations (n) in the dataset. Thus, it provides a standardized measure of the predictive ability of equations, differing in n and p, to account for variation from the mean in the respective data.

The benefit of using weighted regression to homogenize potential variance of residuals was determined by computing and comparing Furnival's Index from both unweighted and weighted regression. Furnival's Index is premised on least squares estimates from unweighted regression being "equivalent to maximum likelihood estimates [mle] under the assumption that the residuals are distributed normally, independently, and with a constant standard error (Johnson and Tetley 1950"; Furnival, 1961). The opportunity exists, then, to select as 'best', the equation with parameter coefficients that maximize the likelihood estimate of the dependent variable in the sample. In a comparison of equations, the equation with the 'best' Index will exhibit residuals most normally distributed, most independent, and with most constant standard error. In constructing Furnival's Index, a likelihood function is formed using the normal probability density function (npdf) in the 'sample space' of the dependent variable. A common sample space for dependent variables that differ due to transformation (e.g., height weighted by unity and height weighted by 1/dbh) is achieved by multiplying the npdf by the first derivative of the function for the dependent variable (e.g., height and height/dbh, respectively). With a common sample space established, the likelihood function is formed using the logical product of the npdf (substituting mean squared error for σ^2). Furnival's method simplifies the likelihood function by removing constants in the logical product of the npdf, taking roots, and inverting the results. This simplification provides relative mle values, rather than, absolute mle values to index the 'best' equation (characterized by the lowest Index value). In unweighted regression (weight of unity), the likelihood estimate is simply the root mean square error (rmse) because the derivative of the function for the dependent variable is one, defaulting the Index to the simplified likelihood function. In weighted regression, the dependent variable is transformed via the weighting scheme, hence, the applicable derivative is other than unity (one), and the resultant Index, other than, simply, the rmse.

The basic form of the equations that were developed have a foundation in current biometric literature, although each have been uniquely adapted to accommodate available independent variables or to be applied more generally. For example, to predict total tree height for trees < breast-height, the Chapman-Ritchard's function (Pienaar and Turnbull 1973) was modified to established lower and upper height asymptotes at 15 and 137 cm, respectively, and to use the independent variables, d15 and z (dummy variable indicating planted tree or wildling tree). Model form and independent variables, while generically similar for any given static tree-level attribute, were customized for specificity to tree species. Stand-level variables were not used as independent variables, as the assembly of stand-level variables was first dependent on the completion of the database .

The prediction of tree height and crown width was separated into two groups: trees < bh and trees > bh. This separation enabled the use of the appropriate stem diameter (d15 or dbh) as an independent variable; bounded the range of prediction within each group; and focused prediction within two diverse periods of tree growth, namely, periods of interspecific competition (among trees and associated vegetation) and intraspecific competition (among trees).

Data for the development of static tree-level equations (tree species specific) were obtained from both the initial and re-measurement (2-year interval) Coastal RVMM database, dependent on a healthy condition code (Chapter 2). For multi-stem rootstocks, the largest d15 or dbh stem (as appropriate) was matched with rootstock height for development of static height prediction equations. For the development of the dbh-d15 relationship, data were obtained dependent on the additional proviso for paired measurements of d15 and dbh for trees with 15 ≤ total height ≤ 300 cm.

3.2.2 Total Tree Height < Breast-Height

Scrivani (1986) describes nine nonlinear model forms to predict height growth development of dominant Douglas-fir in southwestern Oregon. Of these nine equations, three were selected to investigate the prediction of static tree height from 15 cm to 137 cm. This restricted height range was required because field data to be completed involved trees with only a measured d15 which were specifically known to require 15 $\leq$ predicted height $\leq$ 137. The model forms included:

- Chapman-Ritchards (Piennar and Turnbull 1973),

  $Ht = a0 * [1-\exp(a1 * x)]^{a2}$; (1)

- generalized Weibull (Bailey 1980),

  $Ht = a0 * [1-\exp(a1 * x^{a2})]^{a3}$; and, (2)

- 3-parameter Weibull (Yang et al., 1978),

  $Ht = a0 * [1-\exp(a1 * x^{a2})]$; (3)

where,

Ht = total tree height (cm),

exp(f) = e^f (base of the natural logarithm),

x = explanatory variable, and

a0, a1, a2, a3 are coefficients to be determined.

These three equations were selected because their underlying model form is the generalized Weibull with a sigmoid shape and an asymptote parameter (a0). These characteristics appeared useful because a scatter-plot of the data suggested the presence of a sigmoid shape and because the asymptote parameter could be replaced with a constant to provide a desired upper-asymptote for tree height. To establish the upper-asymptote for tree height at 137 cm and to place the origin for tree height and d15 at zero, models (1) to (3) were modified as follows:

- $Ht = 15+\{122 * [1-\exp(a0 * d15)]^{a1}\}$; (1a)
- $Ht = 15+\{122 * [1-\exp(a0 * d15^{a1})]^{a2}\}$; and, (2a)
- $Ht = 15+\{122 * [1-\exp(a0 * d15^{a1})]\}$; (3a)

where,

d15 = basal diameter (mm) at 15 cm above the ground, and

other terms are as defined previously. In equations (1a) to (3a), the constant, 122, replaced the asymptote parameter (a0) in equations (1) to (3), which in conjunction with the shift of the y-axis to 15 cm, produced the desire upper-asymptote for total tree height at 137 cm.

Because Douglas-fir appeared in the database as both a planted tree and a wildling tree, equation (1a), after demonstrating its usefulness over equations (2a) and (3a), was modified to accommodate a dummy variable to indicate a planted tree or a wildling tree. This modification resulted in the following equation:

- Ht = 15+{122 * [1-exp (a0 * d15)]^(a1+a2 * z)}, (1b)

where,

z = 0 for a planted seedling; 1 for a wildling tree,

^ = raised to the power, and

other terms are as defined previously. The formulation of equation (1b) reduces to equation (1a) for Douglas-fir wildlings.

3.2.3 Total Tree Height > Breast-Height

Hann and Larsen (1991) describe five nonlinear model forms to predict diameter (dbh) growth of various tree species in southwestern Oregon. The exponential model form was selected to investigate the prediction of static tree height > bh. This model form was selected for its flexibility to include/exclude independent variables (e.g., often, both dbh and crown width were available), and its ability to be fit using linear regression to obtain starting values for nonlinear regression. The generalized exponential model form is:

- $Ht = \exp[a0+a1 * x1^{a2}+...+an * xn^{a(n+1)}]$ (4)

where,

n = the number of potential predictor variables, and

other terms are as defined previously. To place the origin for tree height and dbh at breast-height (137 cm), model (4) was modified as follows:

- $Ht = 137+\exp[a0+a1 * x1^{a2}+...+an * xn^{a(n+1)}]$ (4a)

where, terms are as defined previously.

Because Douglas-fir appeared in the database as both a planted tree and a wildling, equation (4a) was modified to accommodate a dummy variable to indicate a planted tree or wildling trees:

- $Ht = 137+\exp\{a0+a1 * [x1\text{^}(a2+a3 * z)]\}$, (4b)

where, terms are as defined previously. The formulation of equation (4b) defaults to equation (4a) for Douglas-fir wildlings.

For COCO, the exclusion of the intercept coefficient, a0, in equation (4a) demonstrated a usefulness in statistical fit and prediction over its inclusion, i.e.,:

- $Ht = 137+\exp[a0 * x1^{a1}+...+an * xn^{a(n+1)}]$, (4c)

where, terms are as defined previously.

3.2.4 Single-Stem Diameter

An allometric model relating two tree components on a constant proportional basis was introduced by Kittredge (1944):

- $Y = a0 * x^{a1}$, (5)

where,

Y = tree component to be predicted (e.g., d15), and other terms are as defined previously. A modification by Ruark (1987) to the allometric model, included an additional term enabling two tree components to be related on a variable proportional basis:

- $Y = (a0 * x1^{a1}) * \exp(a2 * x1)$, (6)

where, terms are as defined previously. The need or benefit (e.g., a greater variety of curve shapes) from proportional allometrics is indicated by a statistical significance from zero of the a2 coefficient in equation (6). If the a2 coefficient is not statistically different from zero, equation (6) defaults to equation (5).

In the present study, to use the concept of variable proportional allometrics (i.e., a greater variety of curve shapes) between tree components, but to extend the concept beyond one explanatory variable (e.g., often, both stem diameter and crown width were available), trial and error modifications to equation (6) produced four equations with usage dependent on the species of interest:

- $Y = a0 * x1^{\wedge}(a1 * x2^{a2})$, (7)
- $Y = a0 * x1^{\wedge}(a1+a2 * z)$, (8)
- $Y = a0 * \exp(a1 * x1)$, (9)
- $Y = a0 * \exp[a1 * x1^{\wedge}(a2 * x2)]$, (10)

where, terms are as defined previously.

Equation (7) proved useful for RHPU and SALI; equation (8) for PSME; equation (9) for TSHE, and equation (10) for PREM;

where,

Y = d15 (mm),

X1 = Ht-15 (cm),

X2 = crown width (cm), and

other terms are as defined previously.

For PREM, based on investigations for an equation to predict d15, equation (7) was found useful to predict dbh (Y) as a function of (Ht-137, x1) and crown width (x2).

3.2.5 Multi-Stem Basal Area

Based on investigations for an equation to predict d15, Equation (10) was found useful to predict either ba_d15 or ba_dbh (basal area at d15 or dbh, respectively), as a function of (Ht-15 or Ht-137, respectively, x1) and crown width (x2).

3.2.6 Crown Width

Based on investigations for an equation to predict d15, Equation (7) was found useful to predict PSME crown width (Y) as a function of Ht (x1) and d15 (x2) for trees < bh. However, a modification of the basic allometric equation (5), to include the number of stems (nstems) on a rootstock, proved most useful for ACCI and RHPU:

- $Cw = (a0 * d15^{a1}) * (nstems^{a2})$, (11)

where,

Cw = crown width (cm), and

other terms are as defined previously.

For trees > bh, the basic allometric equation (5) proved most useful for ALRU, PISI, and TSHE (dbh, x1); equation (8) for PSME (dbh, x1); and equation (11) for ACCI (dbh, x1; nstems, x2); where, other terms are as defined previously.

3.2.7 Dbh-d15

For TSHE, based on investigations for an equation to predict d15, equation (10) was found useful to predict dbh as a function of d15 (x1) and Ht (x2).

For hardwood species, a modification of equation (10), incorporating species-specific dummy variables, was found useful:

- $D = (a0+a3 * h + ... + an * h) * exp\{a1 * [d15^{(a2 * Ht)}]\}$, (12)

where,

D = dbh (mm),

h = 1 for a given species in a set of different species; otherwise = 0, and other terms are as defined previously.

For PSME, equation (12) was reduced to explicitly provide specificity to a Douglas-fir planted tree or wildling tree:

- $D = (a0+a3 * z) * exp\{a1 * [d15^{(a2 * Ht)}]\}$, (13)

where, terms are as defined previously.

3.3 Results

3.3.1 General

Table 13 summarizes predicted attributes, species, sample size, explanatory variables, and adjusted R^2 values for the static tree-level equations described in Sections 3.2.2 - 3.2.7. Appendices 2 to 8 present additional, detailed regression statistics (e.g., Furnival's Index and parameter coefficents) for these equations.

A detailed examination of three static tree-level height equations is presented in Sections 3.3.2-3.3.4. Static tree-level equations for total tree height of PSME and ALRU were selected for presentation because these tree attributes and species are of major interest to the RVMM. The examination reflects the statistical considerations used as criteria for acceptance of all equations.

Table 13. Summarized Values for the Static Tree-Level Equations.

Dependent Variable	Species	Sample Size	Explanatory Variables	Adjusted R^2
d15	PREM	134	ht-15 and cw	0.59
	RHPU	38		0.75*
	SALI	24		0.46*
	TSHE	29	ht-15	0.52
	PSME	894	ht-15 and z	0.77
dbh	PREM	121	ht-137 and cw	0.93
ba_d15	ACCI	46	ht-15 and cw	0.53
ba_dbh	ACCI	135	ht-137 and cw	0.56
	COCO	93		0.92
	RHPU	34		0.81
ht < bh	ACCI	87	d15	0.57*
	PREM	95		0.61
	RHPU	56		0.76
	TSHE	29		0.78
	PSME	894	d15 and z	0.80
ht > bh	ACCI	185	dbh	0.72
	ALRU	259		0.83
	PISI	34		0.83*
	PREM	130		0.92
	RHPU	85		0.87
	TSHE	306		0.87
	ALRU	253	dbh and cw	0.86
	COCO	101		0.75
	RHPU	79		0.87
	PSME	5022	dbh and z	0.91

Table 13, Continued: Summarized Values for the Static Tree-Level Equations.

Dependent Variable	Species	Sample Size	Explanatory Variables	Adjusted R^2
cw: trees < bh	ACCI RHPU	136 78	d15 and nstems	0.81 0.59*
	PSME	820	ht and d15	0.86
cw: tree > bh	ACCI	176	dbh and nstems	0.59
	ALRU PISI TSHE	329 64 330	dbh	0.69 0.79 0.90
	PSME	3982	dbh and z	0.90
dbh-d15 relationship	HDWD	176	d15, ht, and species dummy variable	0.74*
	TSHE	24	d15 and ht	0.82
	PSME	367	d15, ht, and z	0.89

* One or more coefficients not significantly different from 0 or 1 at ≥ 95%.

3.3.2 Douglas-fir Total Tree Height < Breast-Height

Figure 7 presents data points and regression lines (equation 1b) to predict Douglas-fir total tree height < bh as a function of basal diameter (d15). The equation incorporates a dummy variable providing specificity to planted trees and wildlings. The dataset comprised 894 observations (769 planted trees, 125 wildling trees) with a range in d15, 1 to 34 mm; and height, 16 to 136 cm. The weighted (1/predicted) regression had a lower Furnival's Index than unweighted, and an adjusted R^2 of 0.80. All least squares coefficient estimates were significantly different from 0 and 1 at 95%.

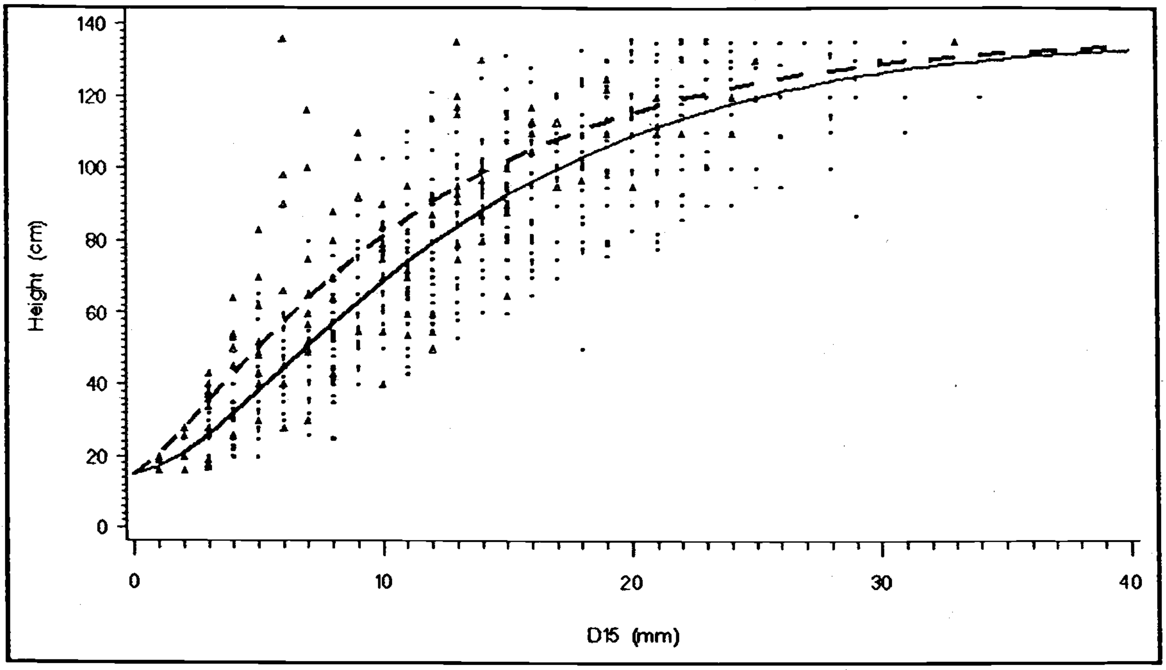

Figure 7. Data points (n=894) and regression lines for Douglas-fir total tree height less than breast-height (equation 1b). Planted: data (dot), regression line (solid). Wildling: data (triangle), regression line (dashed).

For a given basal diameter, predicted height is greater for wildlings than for planted trees (Figure 7). The greatest difference in height between wildlings and planted trees is 13.4 cm, which occurs when d15 is 7.4 mm. Breast-height (137 cm) is achieved by wildlings and planted trees when d15 is 57.1 mm and 60.1 mm, respectively.

Figure 8 presents unweighted height residuals (actual minus predicted) by predicted height. Residuals are centered about zero, although a departure from homoskedasticity (i.e., constant error variance) is indicated by the 'funnel-shape' nature of residuals from predicted height 20 cm to about 60 cm. Furnival's Indices from unweighted and weighted (1/predicted) regression were 14.68 and 14.23, respectively (Appendix 4). The lower ('better') Index value for weighted regression confirms that a degree of heterskedasticity (i.e., non-constant error variance) was present and able to be ameliorated via weighed regression.

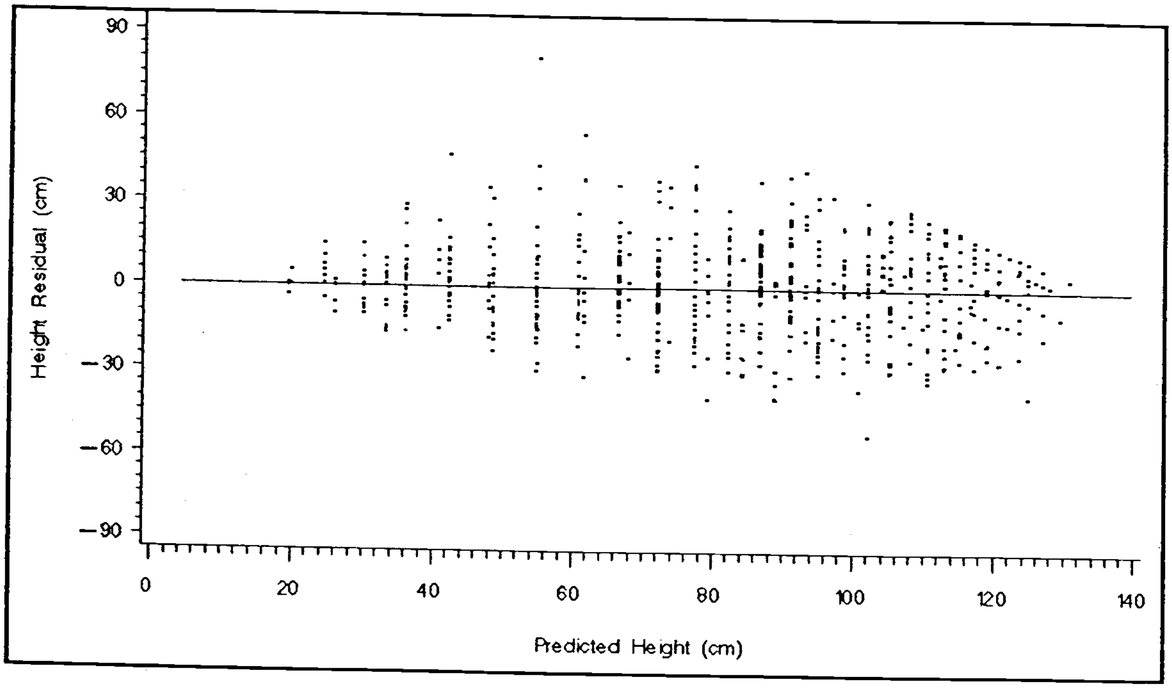

Figure 8. Height residuals by predicted height for Douglas-fir total tree height less than breast-height (equation 1b, unweighted).

Figure 9 presents mean height residuals (as a percentage of predicted height) from the unweighted and weighted regressions plotted against mean d15. These axis variables provide units of measure with a common scale for direct comparison of residuals and error variance from unweighted and weighted regression. Mean residuals are based on 15 groups across the range of basal diameter (d15) represented in the regression dataset. The number of groups used was predicated on obtaining adequate (i.e., of similar magnitude) sample size (range, 32 to 93) across groups. Figure 9 indicates that a more constant error variance was achieved via weighted regression, i.e., the least squares parameter coefficients are more efficient (smaller dispersion).

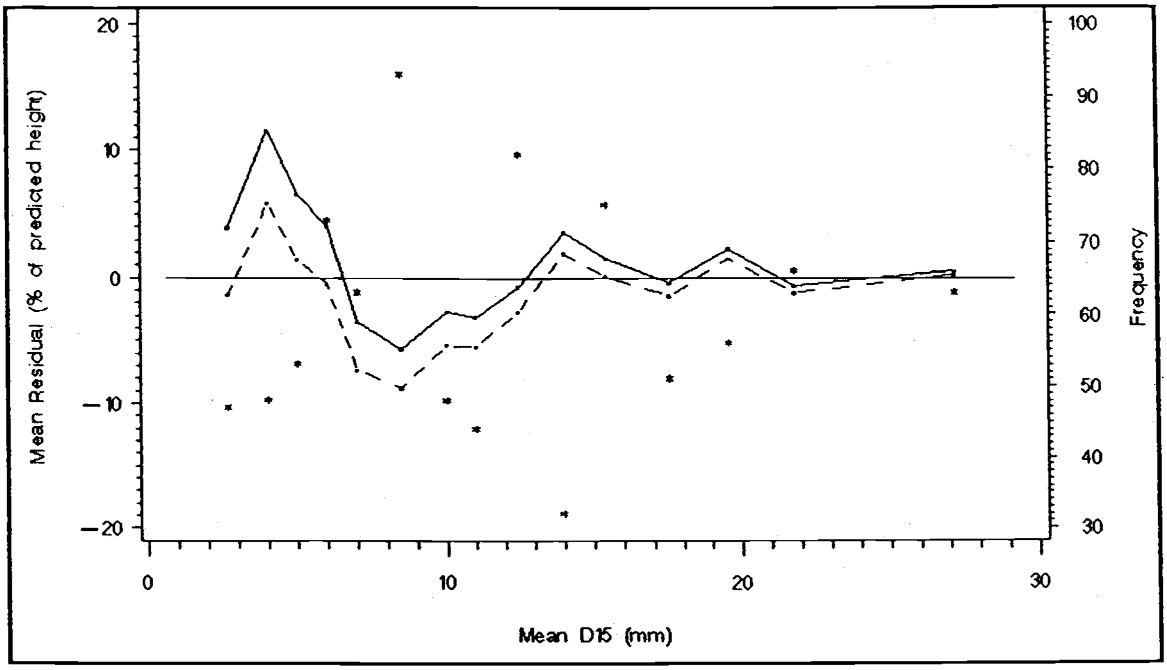

Figure 9. Mean height residuals (as a percentage of predicted height) by mean D15 for Douglas-fir total tree height less than breast-height (equation 1b). Unweighted: solid line. Weighted: dashed line. Frequency: star symbol.

3.3.3 Douglas-fir Total Tree Height > Breast-Height

Figure 10 presents the data points and regression lines (equation 4b) to predict Douglas-fir total tree height > bh as a function of dbh. The equation incorporates a dummy variable providing specificity to planted trees and wildlings. The dataset comprised 5022 observations (4610 planted trees, 412 wildling trees) with a range in dbh, 3 to 332 mm; and height, 138 to 1785 cm. The weighted (1/dbh) regression had a lower Furnival's Index than unweighted, and an adjusted R^2 of 0.91. All least squares coefficient estimates were significantly different from 0 and 1 at $\geq$ 95%.

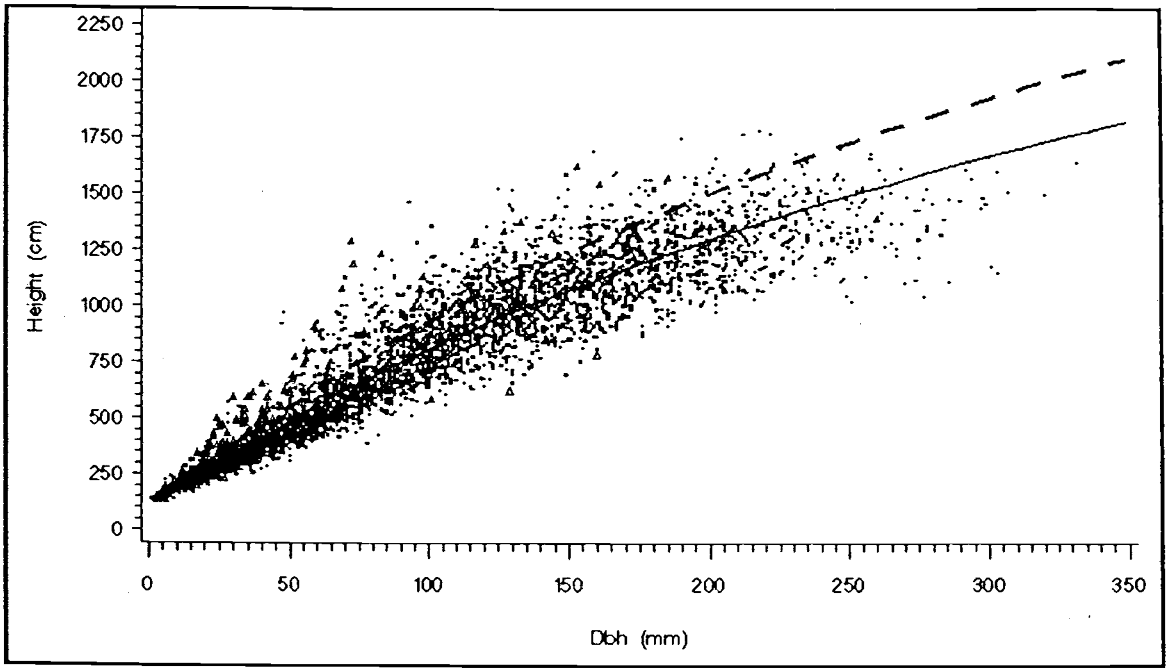

Figure 10. Data points (n=5022) and regression lines for Douglas-fir total tree height greater than breast-height (equation 4b). Planted: data (dot), regression line (solid). Wildling: data (triangle), regression line (dashed).

Figure 10 illustrates that for a given dbh > 1, predicted height is greater for wildlings, than for planted trees. A close inspection of the curves reveals that this height differential exists only for dbh > 1. For 0 < dbh < 1, the differential is reversed, and for dbh = 1, the differential is zero. This reversal and equality is a function of the form of equation (4b) and the data to which it was fit. In the dataset, dbh is always $\geq$ 1 because the precision of measuring dbh was to the nearest 1 mm. The equation, then, is only appropriate for dbh $\geq$ 1. For dbh approaching 1 from below, planted PSME and wildlings are both, by definition, at breast-height (137 cm). Thereafter, as dbh increases throughout the dbh range of the data (3 $\leq$ dbh $\leq$ 332 mm), the height differential increases and culminates at 2.74 meters.

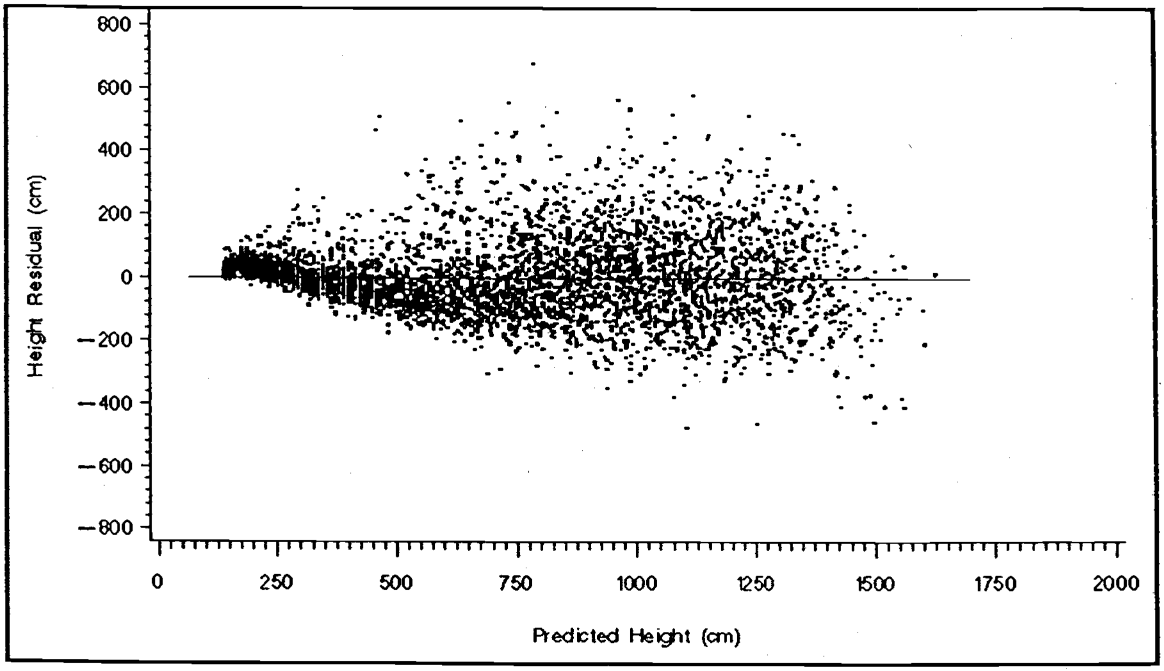

Figure 11. Height residuals by predicted height for Douglas-fir total tree height greater than breast-height (equation 4b, unweighted).

Figure 11 presents unweighted height residuals (actual minus predicted) by predicted height. Residuals are centered about zero, although a departure from homoskedasticity (i.e., constant error variance) is indicated by the 'funnel-shape' nature of residuals 137 < predicted height ≤ 675 cm. Furnival's Indices from unweighted and weighted (using 1/dbh) regression were 115.26 and 90.73, respectively (Appendix 5). The lower ('better') Index value for weighted regression confirms that a degree of heteroskedasticity (i.e., non-constant error variance) was present and able to be ameliorated via weighed regression.

Figure 12 presents mean height residuals (as a percentage of predicted height) from the unweighted and weighted regressions plotted against mean dbh. These axis variables provide units of measure with a common scale for direct comparison of residuals and error variance from unweighted and weighted regression. Mean residuals are based on 15 groups across the dbh range represented in the regression dataset. The number of groups used was predicated on obtaining adequate (i.e., of similar magnitude) sample size (range, 228 to 266 observations) across groups. Figure 12 indicates that a more constant error variance was achieved via weighted regression, i.e., the least squares parameter coefficients are more efficient (of smaller dispersion).

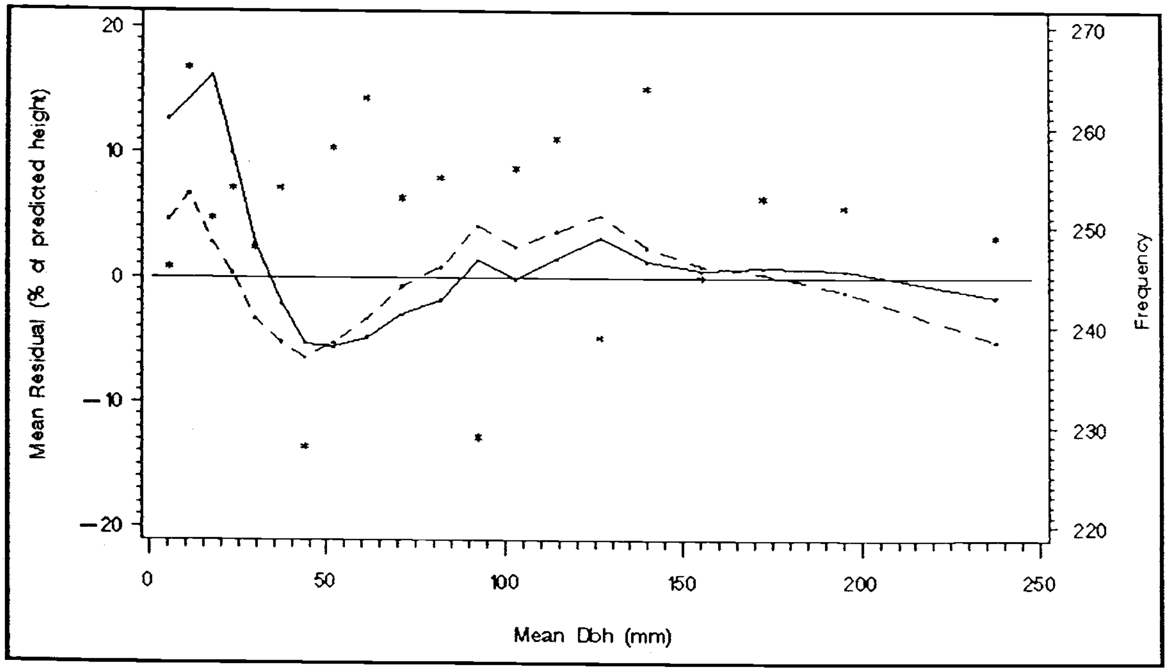

Figure 12. Mean height residuals (as a percentage of predicted height) by mean Dbh for Douglas-fir total tree height greater than breast-height (equation 4b). Unweighted regression: solid line. Weighted regression: dashed line. Frequency: star symbol.

3.3.4 Red Alder Total Tree Height > Breast-Height

Figure 13 presents the data points and regression line (equation 4a) to predict red alder (ALRU) total tree height > bh as a function of dbh. The dataset comprised 259 observations with a range in dbh, 4 to 212 mm; and height, 153 to 1605 cm. The weighted regression had a lower Furnival's Index than unweighted, and an adjusted R^2 of 0.83. All least squares coefficient estimates were significantly different from 0 and/or 1 at $\geq$ 95%.

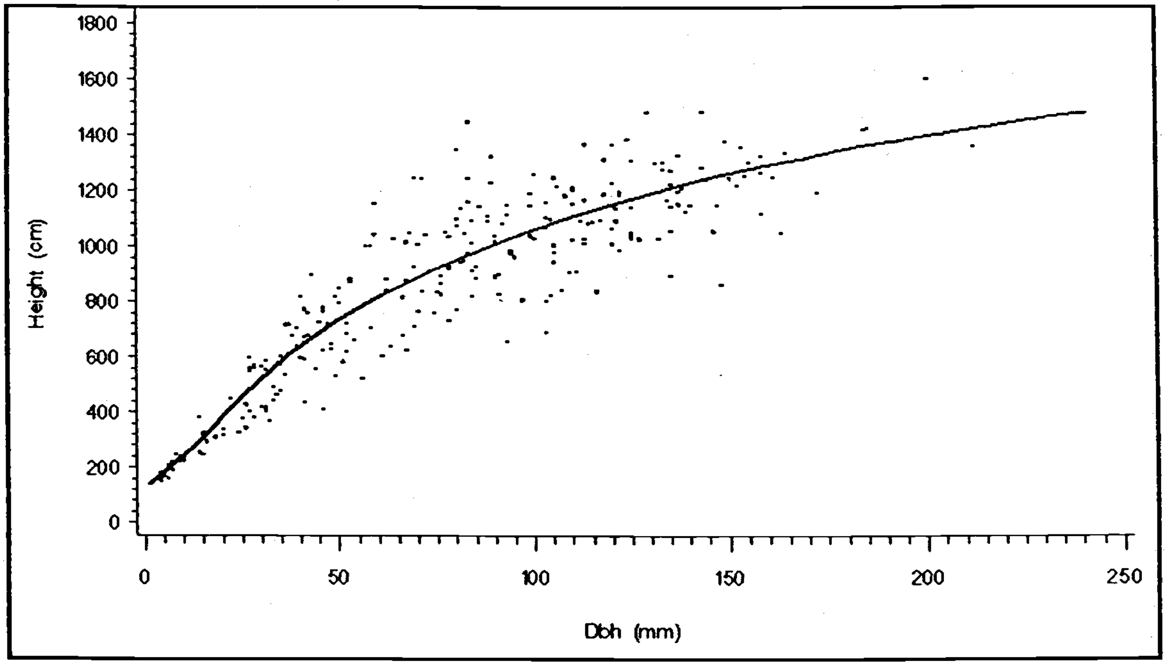

Figure 13. Data points (n=259) and regression lines for red alder total tree height greater than breast-height (equation 4a, unweighted).

Figure 14 presents unweighted height residuals (actual minus predicted) by predicted height. Residuals are centered about zero, although a departure from homoskedasticity (i.e., constant error variance) is indicated by the 'funnel-shape' nature of residuals 137 < predicted $\leq$ 800 cm. The lower ('better') Index value for weighted regression confirms that a degree of heterskedasticity (i.e., non-constant error variance) was present and able to be ameliorated via weighed regression.

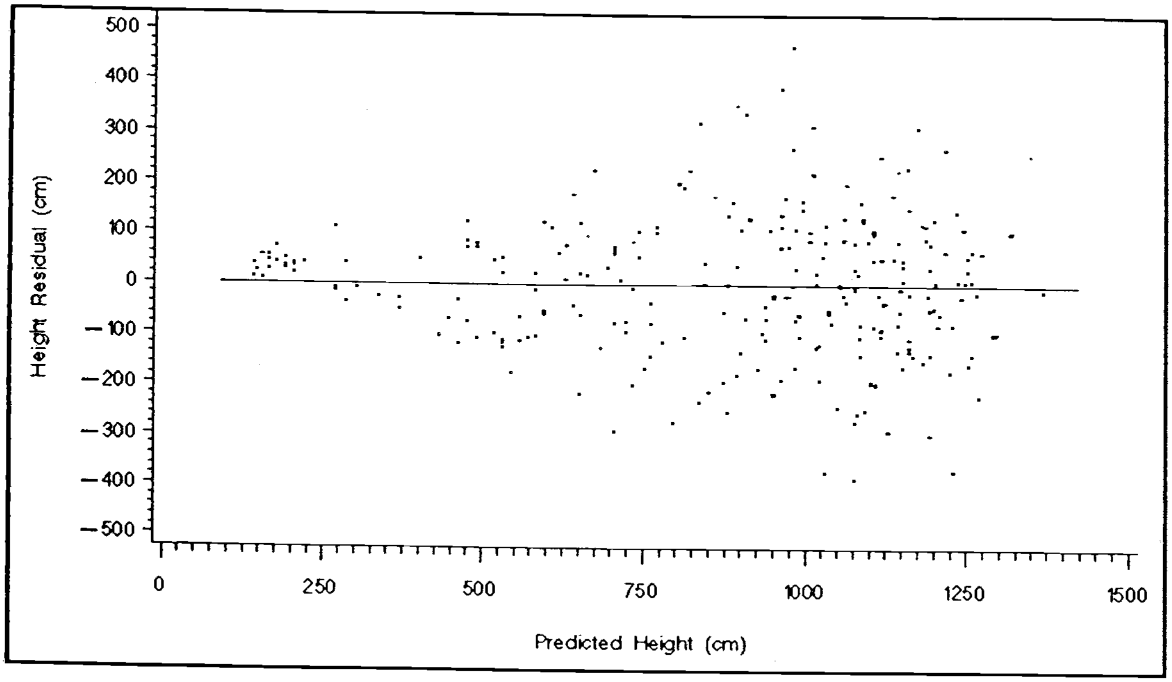

Figure 14. Height residuals by predicted height for red alder total tree height greater than breast-height (equation 4a, unweighted).

Figure 15 presents mean height residuals (as a percentage of predicted height) from the unweighted and weighted regressions plotted against mean dbh. These axis variables provide units of measure with a common scale for direct comparison of residuals and error variance from unweighted and weighted regression. Mean residuals are based on 15 groups across the dbh range represented in the regresssion dataset. The number of goups used was predicated on obtaining adequate (i.e., of similar magnitude) sample size (range, 11 to 14 observations) across groups. Figure 15 indicates that a more constant error variance was achieved via weighted regression, i.e., the least squares parameter coefficients are more efficient (smaller dispersion).

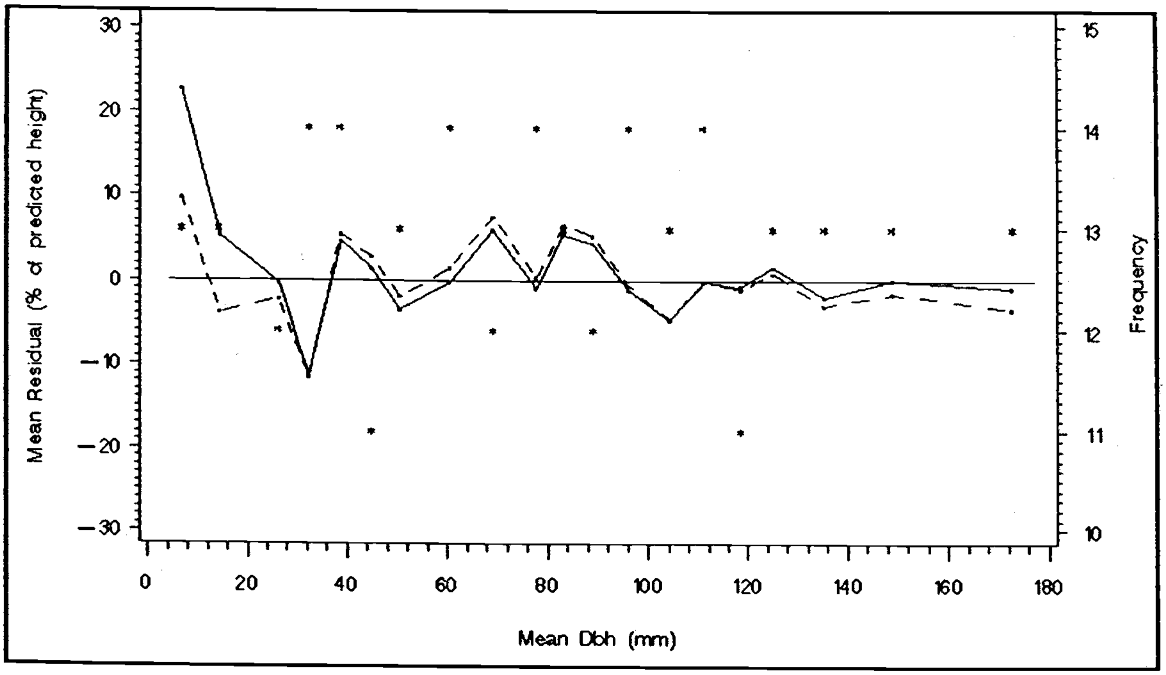

Figure 15. Mean height residuals (as a percentage of predicted height) by mean Dbh for red alder total tree height greater than breast-height (equation 4a). Unweighted regression: solid line. Weighted regression: dashed line. Frequency: star symbol.

3.4 Discussion

3.4.1 General

In total, 36 static tree-level equations were developed to fill-in missing data in the RVMM database. In all but 2 cases (ACCI tree height < bh and TSHE crown width for trees > bh), weighted regression was used to better meet (as indicated by Furnival's Index) a basic assumption of least squares regression, i.e., homogeneous error variance. The equations represent new formulations of equations generally available in biometric literature and yield adjusted R^2 's ranging from 0.46 to 0.93 with a mean of 0.76 and a coefficient of variation of

17%. Over 80% of the equations had all coefficients significantly different from 0 and 1 at $\geq$ 95%.

3.4.2 Total Tree Height

In the prediction of Douglas-fir tree height, a statistically significant ($\alpha = 0.05$) term was included as a dummy variable to specify either a planted tree or a wildling tree. In both situations to predict tree height (trees < bh and trees > bh), wildling trees of the same stem diameter as planted trees were predicably taller (Figures 7 and 10). Because the age of wildling trees were unknown, inferences regarding the height and diameter growth rate of wildlings vs planted trees are inappropriate. A valid inference, however, is that wildlings have a greater height-diameter ratio, than planted trees. This inference suggests that, for wildlings, height increases faster than diameter.

Comparison of the predictions for red alder and Douglas-fir tree height > bh reveals an interesting height-diameter relationship. Figure 16 presents the red alder data points and regression line, along with the Douglas-fir regression line for planted trees. Figure 16 illustrates that, up to about 225 mm dbh and 1400 cm height, red alder is predicably taller than planted Douglas-fir (for trees of the same dbh). The greatest height differential is 260 cm at 69 mm dbh. Red alder, then, (within the range of the RVMM ALRU data) exhibits a greater height:diamter ratio (HDR), than planted Douglas-fir, suggesting that red alder height increases faster than diameter. The more convex shape of the red alder curve, relative to planted Douglas-fir, and the potential junction of the two curves at about 1500 cm indicates that the HDR of red alder increases quickly, then, moderates; while the HDR of planted Douglas-fir increases more steadily (Figure 16). Wildling Douglas-fir has a HDR more closely related to red alder (Figures 10 and 16). Inferences regarding the HDR of red alder beyond 225 mm dbh (i.e. beyond the point where the curves potentially intersect) are inappropriate because this requires extrapolation beyond the data for red alder (maximum dbh = 212 mm).

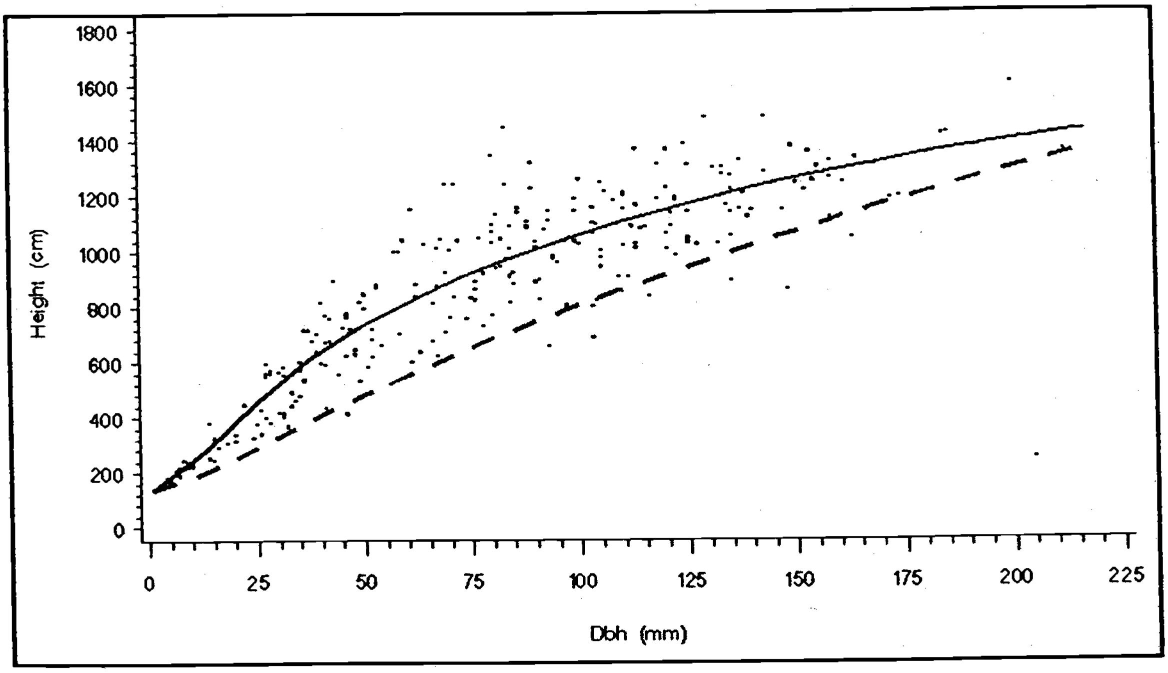

Figure 16. Red alder data points (n=259) and regression lines for red alder and Douglas-fir total tree height greater than breast-height (equation 4a and 4b, respectively). Red alder: data (dot), regression line (solid). Douglas-fir: regression line, planted (dashed).

3.4.3 Single-Stem Diameter

For the prediction of basal diameter (d15), the constant and variable proportional allometric models (equations 5 and 6, respectively) were tried. Each produced lower adjusted R^2s than equation (10), and coefficients that were usually not significantly different than zero (α = 0.05). Thereafter, trial and error modifications to equation (6) resulted in equations (7) to (10).

For prediction of Douglas-fir basal diameter (d15), a statistically significant (α = 0.05) term included in equation (8) is a dummy variable for specificity to either a planted tree or a wildling tree. Figure 17 illustrates that wildling trees of the same total height as planted trees have predictably smaller d15s. The greatest difference in basal diameter between wildlings and planted trees is 5.1 mm, which occurs as tree height approaches breast-height (137 cm). This size differential supports the inference made in Section 3.4.2, i.e., for wildling trees, height increases faster than diameter growth.

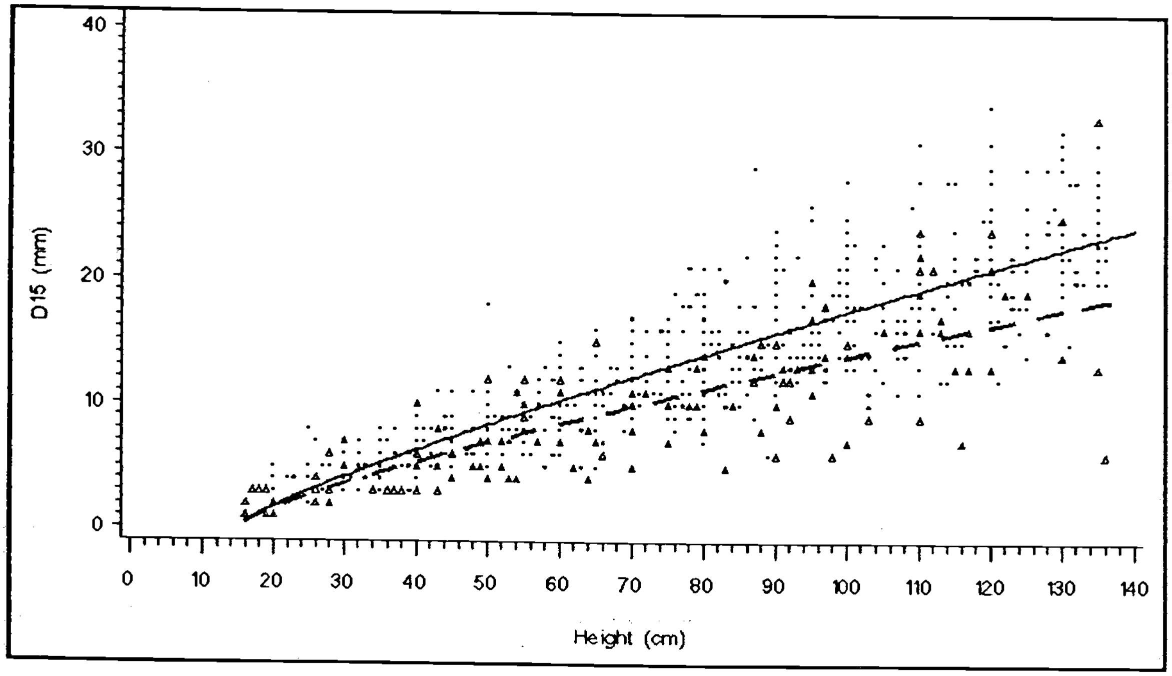

Figure 17. Data points (n=894) and regression lines for Douglas-fir basal diameter at 15 cm (equation 8). Planted: data (dot), regression line (solid). Wildling: data (triangle), regression line (dashed).

3.4.4 Multi-Stem Basal-Area

For prediction of multi-stem rootstock basal area (1 to 5 measured stems per rootstock) at either d15 or dbh, the form of equation (10) was singularly suited to the hardwoods: ACCI, COCO, and RHPU. While the explanatory variable, total number of stems per rootstock, was tried, rootstock total crown width provided higher adjusted R^2 values and consistently significant coefficients ($\alpha = 0.05$).

For prediction of rootstock basal area at dbh; coefficients a1 and a2 for ACCI, COCO, and RHPU are similar in sign and magnitude (Appendix 3). However, the a0 coefficients for these species vary in magnitude: 40, 151, and 262, respectively. Therefore, for trees of same height and crown width, predicted rootstock basal area (1 to 5 measured stems per rootstock) by species increases in magnitude similarly. An inference is that this variation in species' rootstock basal area reflects the species' relative variation in diameter increment, i.e., ACCI lowest and RHPU highest, for trees of same height and crown width.

3.4.5 Crown Width

To predict the crown width of ACCI and RHPU (trees < bh), the number of stems (nstems) on the rootstock was a statistically significant ($\alpha \geq 0.05$ and 0.07, respectively) explanatory variable to include in equation (11). This equation is a modification of the constant allometric model (equation 5), and includes a second explanatory variable with the rate parameter assumed to be 1, and the a2 coefficient, a shape parameter to be determined. For Douglas-fir trees > bh, tree height replaced nstems as a statistically significant ($\alpha \geq 0.05$) explanatory variable to include in equation (7). While this equation has the form of the basic allometric model (equation 5), the shape parameter in equation (5) was expanded to include rate (a1) and shape (a2) parameters. Although specificity to either a planted or wildling tree was checked, this dummy variable was not a statistically significant ($\alpha \geq 0.05$ and 0.07, respectively) explanatory variable to include in the prediction equation.

For ALRU, PISI, and TSHE; the constant proportional allometric model (equation 5), without the use of nstems, successfully predicted the crown width of trees > breast-height. For Douglas-fir, modifying equation (5) with the inclusion of a dummy variable for specificity to either a planted tree or a wildling tree was a statistically significant ($\alpha = 0.05$) term to include in the prediction model (equation 8). A wildling tree of the same dbh as a planted tree has a predictably smaller crown width. The ranking of predicted crown width from largest to smallest for trees of same dbh is: ALRU, PSME (planted), PSME (wildling), TSHE, and PISI. Alternatively for ACCI, equation (11) successfully predicted crown width for trees > breast-height, as similarly for ACCI < breast-height.

3.4.6 Dbh-D15

Equations 10 (TSHE), 12 (HDWDs), and 13 (PSME) are similar in form to predict dbh primarily as a function of d15 and height. In equations (12) and (13), the a0 coefficients are effectively 'modified' by the 'tree of interest' (e.g., a particular hardwood species, or a planted or wildling PSME, respectively). Equation (10) does not include a modification to the a0 coefficient. In each of the equations, the second term has identical form. The ranking of predicted dbh from largest to smallest for trees of same d15 and height is: PSME (wildling), PSME (planted), ACCI, RHPU, TSHE, COCO, and PREM. In contrast, this ranking reflects the extent of stem taper (from d15 to dbh), from smallest to largest, for these species (tree height $\leq$ 300 cm).

Chapter 4: Douglas-fir Juvenile-Stand Height Potential Index

4.1 Background

A Douglas-fir juvenile-stand height potential index equation was developed to meet two objectives: (i) to allow juvenile-stand height index determined from Coastal RVMM to be used in rotation-age growth models, and (ii) to provide an explanatory variable to predict individual-tree growth. Because one use of Coastal RVMM is to be a 'front-end' growth model for existing rotation-age growth models (e.g., ORGANON, Hann et al., 1995), it is necessary to obtain an index of inherent site productivity, or height potential for young- (1 ≤ breast-height-age ≤ 10) to juvenile-aged (11 ≤ breast-height-age ≤ 20) managed plantations. Existing site index curves (e.g., King, 1961; Bruce, 1981; Means and Sabin, 1989) are not well suited to young/juvenile managed stands because these models were developed using datasets either limited in data from young stands (Hann, 1996) and/or obtained from stands originating from natural seed-fall and developmental conditions. The base-age for such site index curves is 50 years breast-height-age. Conversely, the RVMM database is especially tailored to young, managed plantations, whereby a base-age of 20 years would more appropriately apply. Thus, with relatively little effort, the database of the age range of the juvenile-stand height potential could be extended to include datasets from older, managed plantations, broadening the base of the height potential function to 'dove-tail' with older rotation-age models.

The prediction of individual-tree growth often has used a combined approach (Quicke et al., 1994), wherein maximum expected growth is subsequently modified by explanatory variables pertinent to an individual tree, e.g. tree size (stem diameter and height) and position in the stand (basal-area in trees larger than the subject tree). The development of a juvenile-stand height growth function in Coastal RVMM provides the opportunity to apply the function to any individual-tree at two points in time (a desired growth interval), as if it were a dominant tree, and so, obtain a tree's maximum expected, or potential height growth.

4.2 Database

Stand age, sampling intensity, and stand management exclusive of fertilization were the primary requirements for inclusion of datasets in the database to develop the juvenile-stand height potential index equation.

Stand Age. A minimum stand age requirement pertains to trees at least above breast-height, i.e., breast-height-age ≥ 1 year. The maximum stand age requirement was unspecified and left to be determined by the available data. The expectation was to represent a range in stand ages from breast-height-age 1 year through plantation age 20 years. Thus, providing a database tailored to young/juvenile stands, yet concomitantly, conditioned to older stands, as well, i.e., stands for which estimates of site index are to be used in existing, rotation-age growth models.

Sampling Intensity. The Sampling intensity requirement restricted any dataset to those developed from a sampling scheme that would permit the selection of dominant trees on a unit-area basis (e.g., 99 tallest trees per hectare, or 40 trees per acre). This requirement was established to ensure that the selection of dominant trees was consistently applied across different datasets, and reproducible in the field upon subsequent acceptance/utilization of the juvenile-stand height potential index.

Stand Management. The stand management requirement to exclude fertilized stands was included to provide a uniform, stable base across different datasets to interpret juvenile-stand height potential without the confounding effects of fertilization. While the Coastal RVMM dataset was the foundation of the database for the juvenile-stand height potential index equation, four other datasets contributed to the breadth of the overall database with regard to stand age and site quality. Individual-tree data meeting the selection criteria to develop the height potential index equation came from the Oregon State University cooperative, Coordinated Research on Alternative Forestry Treatments (CRAFTS); the USFS-PNW Research Station (Corvallis, Oregon and Olympia, Washington); and the University of Washington, Stand Management Cooperative.

4.2.1 Regional Vegetation Management Model (RVMM)

The database to develop Coastal RVMM originated from the establishment of growth monitoring plots according to a specified matrix incorporating site productivity, Douglas-fir height classes, and combinations of site preparation, competition release, and precommercial thinning (Chapter 2). These matrix components were used to guide the representation of species, abundance, and intensity of associated vegetation (Shula and Knowe, 1991b; Shula and Knowe, 1992). Dataset matrix cells were represented by one or more 0.04- to 0.06-ha (0.10- to 0.15-acre) Douglas-fir measurement plots (PMPs) containing four 0.004-ha (0.01-acre) associated vegetation measurement plots (Chapter 2). Nearly 100 unreplicated PMPs were installed in the Coast Range Mountains of Oregon and Washington (from Forks, WA to Coos Bay, OR). All PMPs that met the sampling intensity criteria to characterize dominant height on a unit area basis (Section 4.3.2) were included in the analyses.

4.2.2 CRAFTS Coast Range Competition Release Study (CRCRS)

The Coast Range Competition Release Study was started in 1981 by the Oregon State University cooperative, Coordinated Research on Alternative Forestry Treatments (CRAFTS). The objective of the study was to monitor the effects of chemical and manual vegetation treatments on the growth of Douglas-fir, and is described in detail in Harrington et al. (1995). The study was installed in plantations 2-3 years after planting, and continued until plantations were 10-13 years old. Six study locations from Forks, Washington, to Coos Bay, Oregon were established. Vegetation control treatments comprised one time application of chemical and manual methods, annually repeated manual methods, and an untreated control. Unreplicated measurement plots consisted of bounded areas within each treatment block. All trees in the bounded area were not measured, but rather, 100 trees per plot were subjectively selected, as nearest to a square systematic grid across the plot. All plots that met the sampling intensity criteria to characterize dominant height on a unit area basis (Section 4.3.2) were included in the analyses.

4.2.3 USFS-PNW Coast Range Site Preparation Study (CRSPS)

The Coast Range Site Preparation was started in 1980 by the USFS Pacific Northwest Reseach Station (Corvallis, Oregon). The objective of the study was to monitor the effects of site preparation treatments on the growth of Douglas-fir (Stein, 1995). The study was installed in plantations prior to harvesting, and continued, thereafter until plantations were 16 years old. Four study sites central to Florence, Oregon were established. Site preparation treatments (either singly or in combination) included a control, burning, chemical spray, and manual spot clearing of vegetation. Replicated measurement plots (0.08-ha) were installed within each treatment block. All plots that met the sampling intensity criteria to characterize dominant height on a unit area basis (Section 4.3.2) were included in the analyses.

4.2.4 Levels-of-Growing Stock Cooperative Study (LOGS)

The Levels-of-Growing Stock Cooperative Study was initiated in 1961 by the collaborative effort of USFS Pacific Northwest Research Station and Pacific Northwest Region, Oregon State University, Weyerhaeuser Company, the Washington State Department of Natural Resources, and the Canadian Forestry Service. The objective of the study was to determine the effects of residual growing stock from repeated thinning of Douglas-fir on cumulative wood production, tree size, and growth-growing stock ratios. The study is described by Curtis and Marshall (1986). The study was installed in plantations and natural stands which range in breast-height-age (bhage) from 8 to 56 years, and is on-going. Nine study sites extend from Vancouver Island, British Columbia to Hoskins, Oregon (Coast Range); and Randle, Washington to Tiller, Oregon (Cascades Range). Following an initial calibration thinning, treatment thinnings were applied according to criteria that included increase in crop tree height, levels of residual basal area, and relationships between crop trees and the stand diameter distribution. Replicated measurement plots (0.08-ha) were installed in each treatment block. Coast Range study sites with plots that met the sampling intensity criteria to characterize dominant height on a unit area basis (Section 4.3.2) were included in the analyses.

4.2.5 Stand Management Cooperative (SMC), University of Washington

The Stand Management Cooperative at the University of Washington conducts research to investigate the effects of stocking density (planting density and thinning espacement), pruning, and nutrition on Douglas-fir and western hemlock growth and yield, and wood quality (Stand Management Cooperative, 1997). Membership in the cooperative includes governmental forestry agencies and universities, and private forestry companies. A full range of tree stocking density environments for tree growth are researched through installations in young, juvenile, and maturing plantations. Study sites are located throughout the Coast and Cascade mountain ranges from British Columbia to southern Oregon. Replicated measurement plots (0.08-acre) are installed in treatment blocks. Coast Range study sites with plots that met the sampling intensity criteria to characterize dominant height on a unit area basis (Section 4.3.2) were included in the analyses.

4.3 Methods

4.3.1 General

Site index curves, or dominant height curves, generally originate from three developmental approaches: guide curve, retrospective analysis, and permanent-plots. The present analysis used the permanent-plot approach.

Guide Curve. The guide curve approach was used in early forest growth and yield research in the Pacific Northwest, e.g., the Douglas-fir site index curves in USDA Technical Bulletin 201 (McArdle, Meyer, and Bruce, 1961). This approach uses independently sampled trees or stands for paired height and age data. To these data, a hand-drawn or regression-based guide curve is fit. Thereafter, a family of curves are proportionally placed above and below the central guide curve. If the proportional placement of the family of curves is equal across all ages, the phrase anamorphic in shape is applied, and curve shape is identical across site indices (McArdle, Meyer, and Bruce, 1961). If the proportional placement of the family of curves is not equal across all ages, the phrase polymorphic in shape is applied; curve shape varies by site index. Such polymorphic site index curves have been developed based on fractions or multiples of the standard deviation of height residuals derived from the original guide curve (Brickell, 1968).

Retrospective Analysis. A standing-tree retrospective analysis approach was used to develop Douglas-fir site index curves that are still in use west of the crest of the Cascade mountains in the Pacific Northwest (King, 1966). A felled-tree retrospective approach was successfully applied to Douglas-fir and ponderosa pine in Southwest Oregon (Hann and Scrivani, 1987), and Douglas-fir in western Oregon (Means and Sabin, 1989). The retrospective approach utilizes paired height and age data from standing or felled and stem-sectioned dominant and co-dominant trees. Site index curves, then, are determined by regressing height against age. Either anamorphic or polymorphic curves are produced, dependent on the form of the regression equation.

Permanent-Plot. The permanent-plot approach utilizes permanent growth monitoring plots to provide re-measured height and age paired data from dominant or co-dominant trees. This approach was used by Bruce (1981) to develop site index curves for Douglas-fir in the Pacific Northwest. Site index curves are determined by regression, as described previously for the retrospective analysis approach.

4.3.2 Characterization of Douglas-fir Dominant Height

Douglas-fir dominant height was calculated using the tallest trees > bh at a preferred sampling intensity of 98.8 trees per hectare (40 trees per acre), but an allowable minimum sampling intensity of 74.1 trees per hectare (30 trees per acre). The preferred sampling intensity is the generally accepted standard identified in the previously mentioned site index development literature (Section 4.3.1). The minimum sampling intensity was chosen to allow some latitude in defining dominant height in very young stands.

Trees were selected for inclusion as 'dominant height trees' or 'index-trees' at the beginning of each growth interval represented in the various datasets. This replacement sampling enables any tree meeting or not meeting the selection criteria the opportunity to be re-selected or excluded, respectively. This selection method was chosen in order to characterize site potential, which was considered to be best expressed by the tallest trees represented at the start of each period, not the tallest trees at the start of a series of plot remeasurements. Furthermore, these most dominant trees were assumed to have their height growth least effected by competing vegetation. This assumption does not entirely account for competition effects, nor does it claim to express entirely 'free-to-grow' or 'bare-ground' growing conditions for the dominant trees (Hanson, 1997). Nonetheless, the use of growth data from the most dominant trees > bh from a range of competing vegetation stand conditions was considered to be the best approximation to 'free-to-grow' conditions. Also, the resultant height potential index equation was expected to be used to assess site quality in a similar range of competing vegetation stand conditions.

4.3.3 Algebraic Difference Approach

In the development of static tree-level equations (Chapter 3), the exponential equation form, $y = \exp(a_0 + a_1 * x_1 + \ldots + a_n * x_n)$, was used successfully to predict static tree height. This suggested the use of the exponential equation form as the basis for the juvenile-stand height potential index equation.

The juvenile-stand height potential index equation is an algebraic-difference formulation (Clutter et al., 1983), ADF, of an exponentiated and generalised Schumacher growth equation (Schumacher, 1939). The basic equation is:

$$ht_i = 1.37 + \exp(a0 + a1 \times bhage^{a2}) \qquad [14]$$

where:

ht_i = subject tree height (m),

1.37 = the height (m) intercept commensurate with breast-height, exp(x) = e^x; e is the base of the natural logarithm, and

bhage = breast-height-age (years).

The algebraic-difference formulation transforms equation [14] into an implicit height-growth equation, whereby ht_{i2} (individual-tree height at time2) is predicted as a function of ht_{i1} (individual-tree height at time1), and $bhage_1$ and $bhage_2$ (bhage at time1 and time2, respectively). The steps involved to form a polymorhphic ADF of equation [14] are:

- Isolate a2: algebraically arrange for a2 (results in the shape parameter being site specific; i.e., a2 will no longer be a constant to be determined in the fitted equation);
- Equate: ht_{i2} and $bhage_{i2}$ with ht_{i1}, $bhage_{i1}$ (in terms of a2); and,
- Solve: ht_{i2}, as a function of ht_{i1}, $bhage_{i1}$, and $bhage_{i2}$.

The resultant, fully specified equation [15]:

$$ht_{i2} = 1.37 + \exp\left\{a0 + a1 \times \exp\left\{\ln\left[\frac{[\ln(ht_{i1} - 1.37) - a0]}{a1}\right] \times \left[\frac{\ln(bhage_2)}{\ln(bhage_1)}\right]\right\}\right\}$$

where:

ht_{i1},ht_{i2} = individual-tree total height (m) at time1 and time2,

1.37 = the height (m) intercept at breast-height,

$bhage_1$, $bhage_2$ = bhage (years) at time1 and time2,

exp(x) = e^x; e is the base of the natural logarithm,

ln = natural logarithm, and

a0, a1 = coefficients to be determined.

In practice, to predict juvenile-stand height potential index (HPI), ht_{i2} is replaced with HPI; and $bhage_2$ is replaced with base-age (herein, 20 years). Through algebraic manipulation, equation [15] also predicts the potential height of an index-tree (PH_{i2}) at a given HPI, future bhage, and base-age. To do this, in equation [15], ht_{i2} is replaced with PH_{i2}, ht_{i1} is replaced with HPI, and, the bhages are inverted. Collectively, paired index-tree heights and bhages produce height potential index curves that represent height growth trajectories of index-trees.

The parameters in equation [15] were determined (α=0.05) with SAS (SAS Institute Inc.,1989) weighted, non-linear regression procedure, NLIN, (method=marquardt). Criteria for judging goodness-of-fit included adjusted R^2 (Kmenta,1986) and Furnival's Index (Furnival, 1961).

4.4 Results

4.4.1 Database

For the 5 datasets used to develop the height potential index, 2 datasets (CRSPS and CRCRS) represent 1488 observations with initial mean breast-height-age from 1 to 7 years; one dataset (RVMM) represents 351 observations with initial breast-height-age from 1 to 15 years; and, 2 datasets (LOGS and SMC) represent 1616 observations with initial breast-height-age from 8 to 31 years (Table 14). The 5 datasets collectively (n=3455) provide a relatively balanced continuity in dominant height from 1.4 to 7.8 meters, 1.4 to 15.9 meters, and 7.6 to 33.5 meters, respectively.

Table 14. Measures of central tendencies (mean, standard deviation, coefficient of variation, minimum, and maximum) for breast-height-age and dominant height in the five HPI datasets.

Attribute	CRSPS (n=736)	CRCRS (n=752)	RVMM (n=351)	LOGS (n=1512)	SMC (n=104)
Bhage (yrs)					
Mean	2.7	2.8	9.3	19.8	18.9
Std. Dev.	1.5	1.5	4.2	6.6	7.6
Coef. Var.	53.9	53.0	45.1	33.2	40.2
Minimum	1	1	1	8	8
Maximum	6	7	15	31	26
Height (m)					
Mean	3.4	3.1	8.7	17.7	19.5
Std. Dev.	1.5	1.4	4.2	5.4	6.5
Coef. Var.	44.8	44.2	48.6	30.2	33.4
Minimum	1.4	1.4	1.4	7.6	9.6
Maximum	7.4	7.8	15.9	33.5	30.1
Age Interval (yrs)					
Mean	1.8	2.4	2.0	4.3	2.9
Std. Dev.	0.8	1.7	0	1.1	1.0
Coef. Var.	46.8	69.9	0	26.1	34.3
Minimum	1	1	2	3	2
Maximum	3	5	2	7	4

4.4.2 Equation [15]

Equation [15], unweighted, accounts for 99% of the variation about the mean of dominant height at time2 (Table 15); all parameter coefficients are significantly different than zero and one (α=0.05). The very high adjusted R^2 is attributed to the relatively short prediction interval (2.9 years, weighted average), the large sample size (n=3455), and relatively smooth and continuous dominant height from breast-height (1.37 meters) to 34 meters.

Table 15. Parameter coefficients, standard errors, and adjusted R^2 for equation [15].

a0	a1	Adjusted R^2	Furnival Index	
(standard error)			Not Weighted	Weighted (1/predicted)
9.44906 (0.03717)	-7.47893 (0.02773)	0.99	78.9363	85.8985

In general, height residuals from equation [15] are centrally dispersed about zero without serious signs of prediction bias (Figure 18). Nonetheless, predictive ability at the tree-level ranges ± 5 meters, although the bulk of the residuals are ± 2 meters.

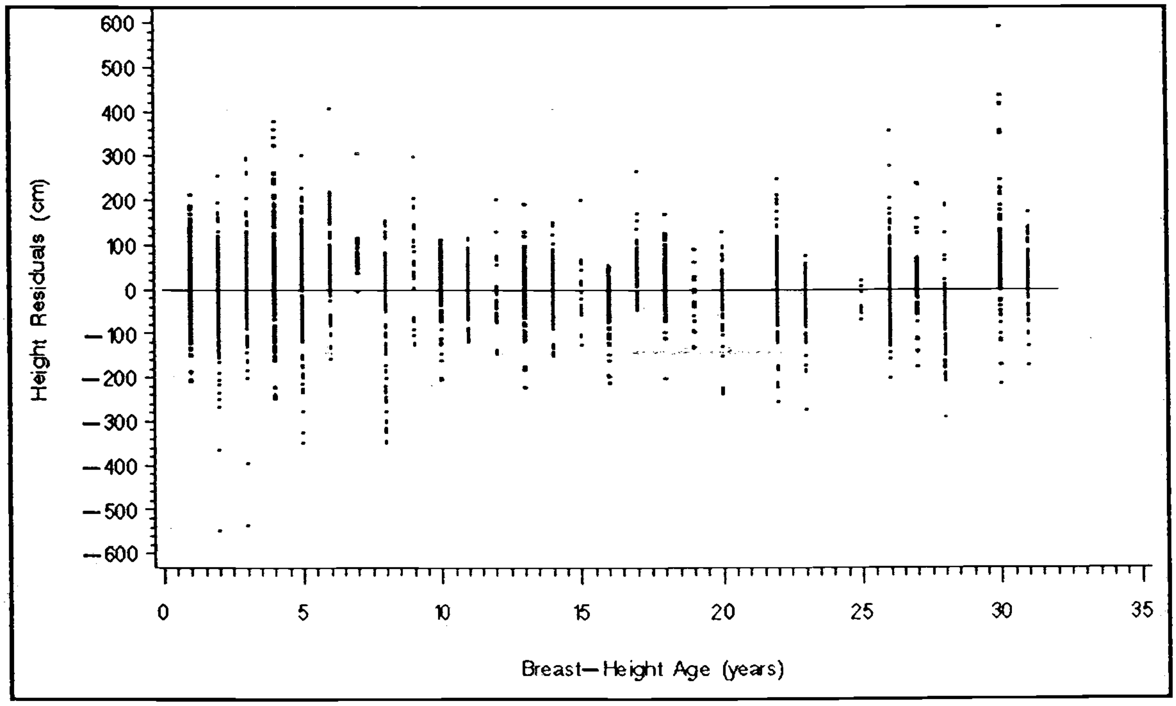

Figure 18. Height residual (centimeters) by breast-height-age (years) from equation [15].

Figure 19 presents mean residuals on the basis of breast-height-age groups with near equal sample size (i.e, frequency). In Figure 19, the dot and star symbols represent 'paired items' which identify 'mean residuals' (the left vertical axis) and the accompanying 'frequency' (the right vertical axis) upon which the mean was calculated, respectively. Figure 19 indicates that, on average, height residuals are centrally dispersed about zero with the bulk of the residuals ± 0.5 meters.

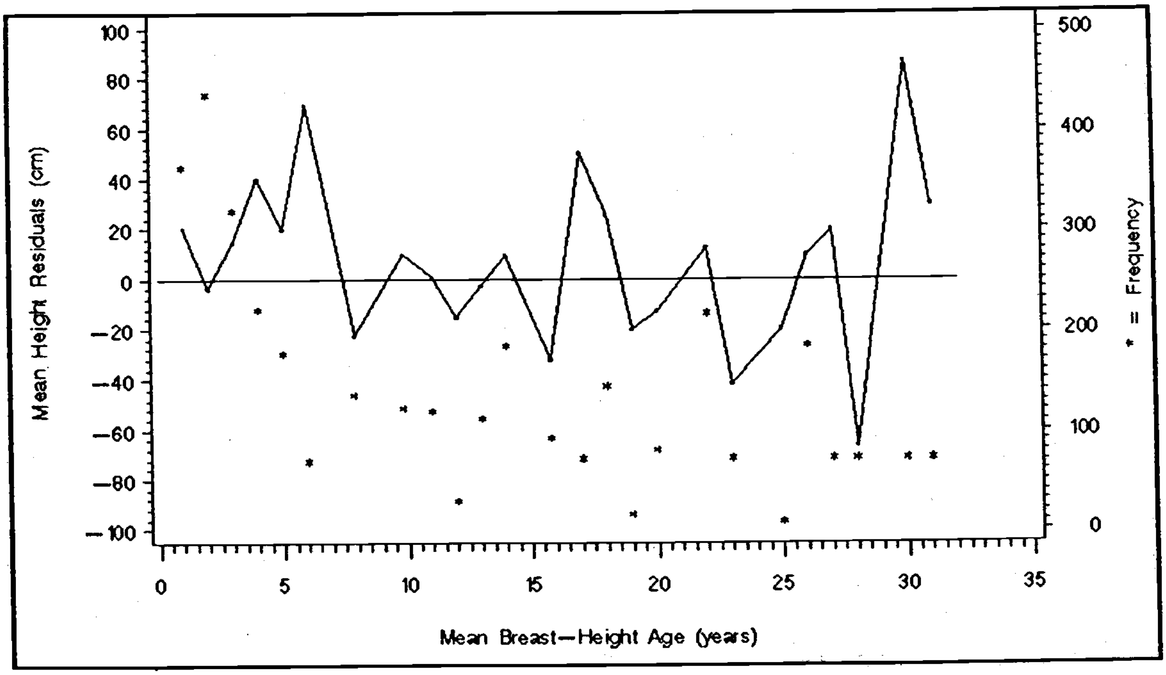

Figure 19. Mean height residual (centimeters) by mean breast-height-age (years). Mean height residual (left vertical axis): solid line. Frequency (right vertical axis): star symbol.

4.4.3 Juvenile-Stand Height Potential Index Curves

Figure 20 presents juvenile-stand height potential index (HPI) curves derived from equation [15] and superimposed over the data. HPI curves (7.5m to 25m) were selected to bracket the lower and upper extremes of the height-bhage data. Base-age is 20 years breast-height, and by example, the 25 meter HPI curve intersects 25 meters tree height at 20 years breast-height-age. Figure 20 illustrates that the HPI curves derived from equation [15] successfully fit the growth trajectories represented in the data.

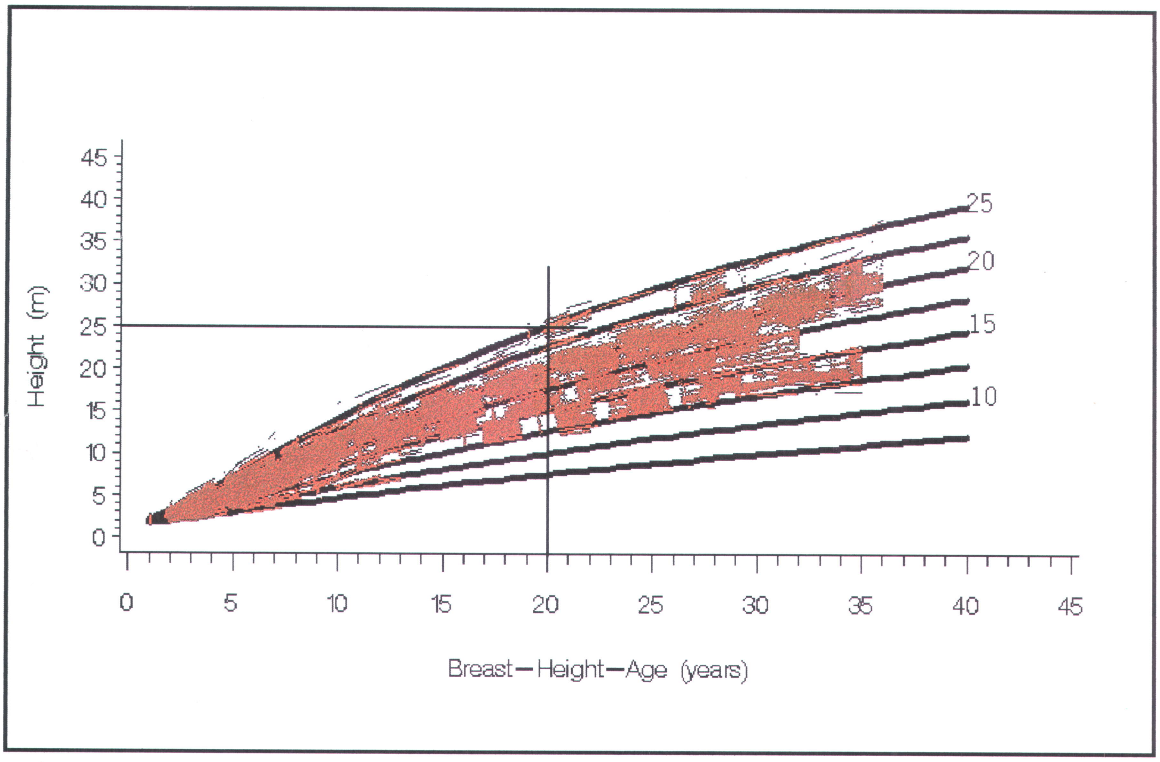

Figure 20. Juvenile-stand height potential index (HPI) curves derived from equation [15] superimposed over the data (n=3455). HPI curves: 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, and 25.0 meters total height at base-age 20 years breast-height-age.

For comparison, Figures 21, 22 and 23 present the height potential index curves (7.5 m to 25 meters at base-age 20 years breast-height) from equation [15] with the site index curves of Bruce (1981), King (1966), and Means and Sabin (1989), respectively. Site index curves for Bruce, King, and Means and Sabin have a base-age of 50 years breast-height. The question arose, then, as to which respective index curves to use for comparison with the HPI curves (base-age 20 years bh). The decision was made to select respective index curves (base-age 50 years bh) for Bruce, King, and Means and Sabin that would pass through potential index height 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, and 25 meters at base-age 20 years bh (Table 16).

Table 16 illustrates that, given the preceding standardization, the differential between HPI and the other indices (at bh age 50 years) increases with increasing site quality. The greatest differential is at the upper-most index curve; Bruce, King, and Means and Sabin is consistently around 51 meters at 50 years breast-height-age; while, in comparison, the corresponding HPI curve is around 44 meters (base-age 50 years bh).

Table 16. Index heights for Bruce (1981), King (1966), and Means and Sabin (1989) site-index curves; and for comparative purposes, the respective index heights for HPI.

HPI	**HPI**	**Bruce**	**King**	**Means & Sabin**
Index Height (m at bhage 20 yrs)	Index Height (m at bhage 50 yrs)			
7.5	13.73	13.66	14.58	15.74
10.0	18.63	19.00	19.92	21.36
12.5	23.32	24.35	25.24	26.77
15.0	27.82	29.75	30.52	32.04
17.5	32.13	35.26	35.77	37.12
20.0	36.28	40.84	41.00	42.05
22.5	40.28	46.38	46.20	46.80
25.0	44.13	51.63	51.37	51.40

Figures 21, 22, and 23 illustrate that the HPI curves represent greater dominant height growth to about bh age 20 years, relative to Bruce, King, and Means and Sabin, respectively.

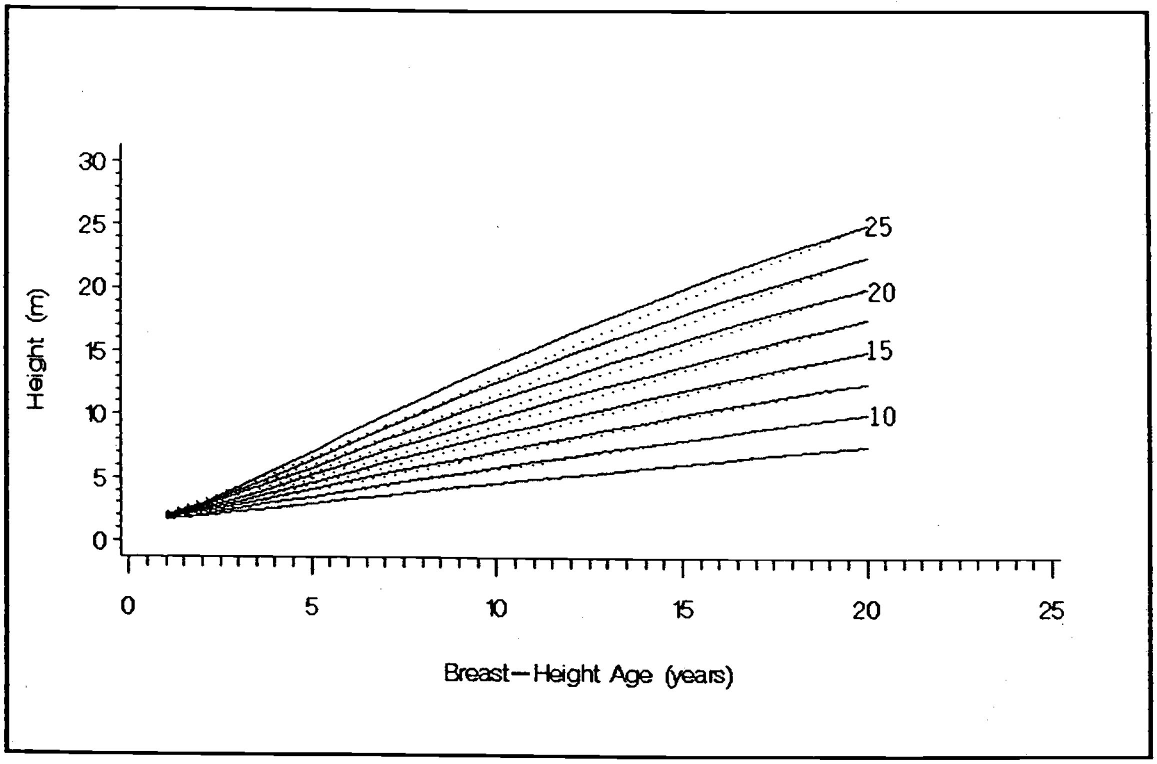

Figure 21. Bruce (1981) Site-Index Curves and HPI Curves from Equation [15]. Index curves: 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, and 25.0 meters total height at 20 years breast-height-age. Bruce curves: dashed lines. HPI curves: solid lines.

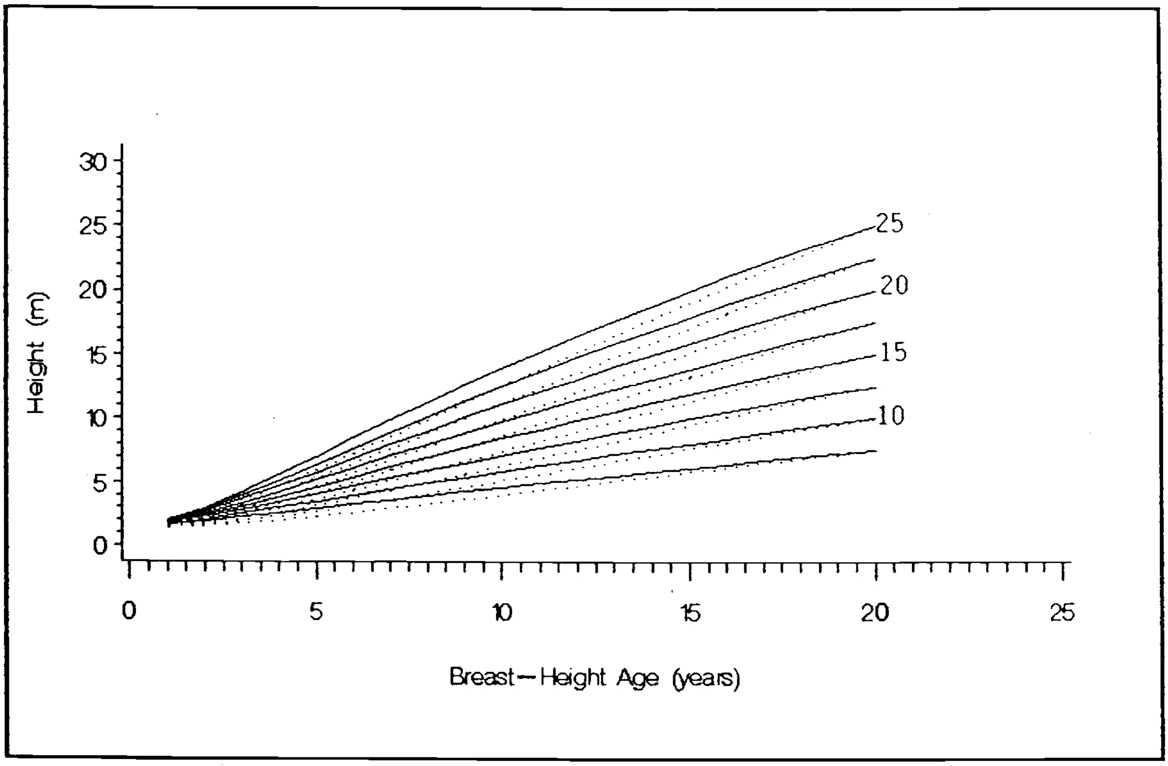

Figure 22. King (1961) Site-Index Curves and HPI Curves from Equation [15]. Index curves: 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, and 25.0 meters total height at 20 years breast-height-age. King curves: dashed lines. HPI curves: solid lines.

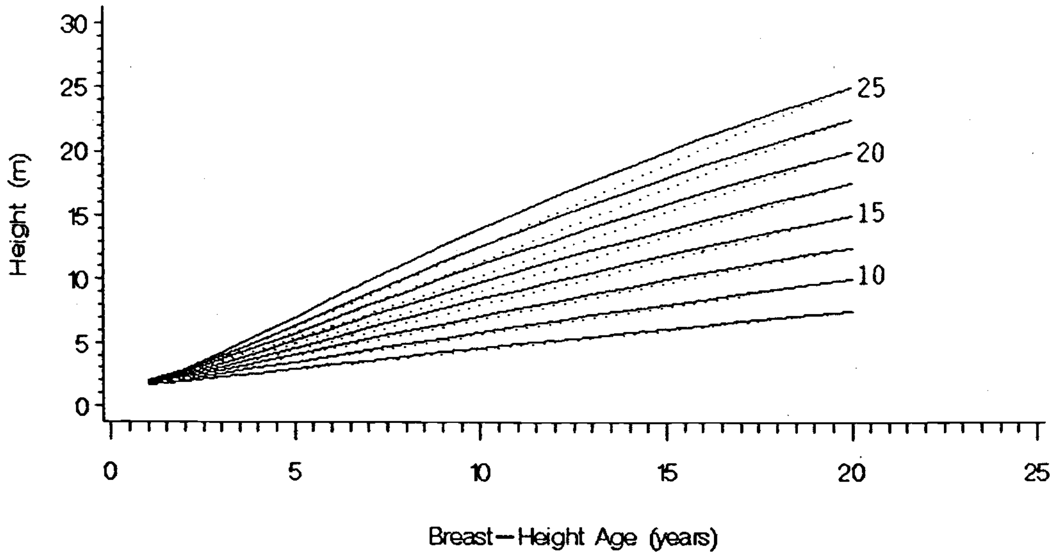

Figure 23. Means and Sabin (1989) Site-Index Curves and HPI Curves from Equation [15]. Index curves: 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, and 25.0 meters total height at 20 years breast-height-age. Means and Sabin curves: dashed lines. HPI curves: solid lines.

4.5 Discussion

4.5.1 General

The juvenile-stand height potential index (HPI) equation [15] permits the user to estimate:

- dominant height at time2, as a function of dominant height at time1, and breast-height-age at time1 and 2;
- HPI, as a function of any base-age, and current breast-height-age and dominant height; or

- index-tree height, as a function of HPI, base-age, and future breast-height-age.

In these respects, the HPI analyses is unique, as it provides especially conditioned dominant height predictive ability for relatively young to older, Pacific Northwest Douglas-fir plantations (≤ 30 years breast-height-age). However, the HPI analyses does not claim to express entirely 'free-to-grow' or 'bare-ground' growing conditions for dominant trees (Hanson, 1997). Nonetheless, the HPI equation is expected to be used to assess site quality in a similar range of competing vegetation stand conditions, as represented in the development database. The HPI equation also enables the derivation of additional explanatory variables (e.g., change in potential height) that can be used in individual-tree growth analyses.

4.5.2 Methods

The HPI analyses used a unique approach to characterize dominant height, in that, the tallest trees were re-selected at the beginning of each growth interval. This selection approach accounted for any interchange of dominant trees on the various plots. By 'sampling with replacement', the dataset of tallest trees repeatedly characterized site-height potential at the beginning of each growth interval.

The use of the algebraic difference approach to formulate the HPI equation provided the means to implicitly include height growth in the determination of site-height potential, rather than simply predicating height potential index on attained height at a given breast-height-age. The algebraic difference approach also provided the flexibility to interchangeably estimate dominate height, HPI, or index-tree height.

4.5.3 Results

The database provides a relatively smooth and continuous display of dominant height from breast-height (1 year above bh) to about 34 meters (31 years above bh). The database also represents a reasonable range in apparent site quality, or site-height potential, as demonstrated by the range in actual data for dominant height from about 5 to 15 meters at breast-height-age 10 years, and 10 to 25 meters at breast-height-age 20 years (Figure 20).

On average, the height residuals are acceptable (Figure 18) and when equation [15] is algebraically rearranged to produce dominant-height-growth curves, the acceptability of equation [15] to implicitly predict height growth is further supported by the agreement of the trajectories of the curves with the raw data (Figure 20).

For breast-height-age ≤ 20 years, HPI curves tend to be above the site index curves of Bruce (1981), King (1966), and Means and Sabin (1989); this trend increases as HPI increases (Figures 21, 22, 23). When compared at breast-height-age 10 years, dominant height on the 25 m HPI curve is 10% greater (4.2 meters) than the average of Bruce, King, and Means and Sabin dominant height. When compared at breast-height-age 50 years, dominant height on the 25 m HPI curve is 14% less (7.3 meters) than the average of Bruce, King, and Means and Sabin dominant height.

Using King (1966) site index curves, Table 17 further demonstrates the contrast between HPI and site index (both with base-age 50 years bh) when calculated on younger and older datasets in the HPI analyses. Clearly, HPI is predicted much more conservatively than King site index for plantations ≤ 15 years breast-height-age (yet, represents greater dominant height growth to about bh age 20 years), and captures greater variability in prediction of site-height potential (i.e., greater and more varied coefficient of variation). For older plantations, HPI underestimates site-height potential relative to King, although HPI is predicted much more consistently across the range in breast-height-age.

HPI captures about the same variability in site-height prediction as King site index.

The comparative differences between the HPI and site index curves presented in the foregoing discussion are attributed to the presence or absence of a bulk of data representing young or old plantations in the respective databases.

Table 17. Measures of central tendencies (mean, standard deviation, coefficient of variation, minimum, and maximum) for HPI and King site Index (both base-age 50 years breast-height) in the 5 HPI datasets.

Attribute	CRSPS (n=736)	CRCRS (n=752)	RVMM (n=351)	LOGS (n=1512)	SMC (n=104)
Bhage (yrs)					
Mean	2.7	2.8	9.3	19.8	18.9
Coef. Var.	53.9	53.0	45.1	33.2	40.2
Minimum	1	1	1	8	8
Maximum	6	7	15	31	26
HPI (m)					
Mean	32.6	27.2	28.4	33.4	38.7
Std. Dev.	13.5	12.3	7.2	4.1	5.6
Coef. Var.	41.4	45.4	25.5	12.2	14.6
Minimum	1.4	1.4	1.4	23.7	29.2
Maximum	80.1	72.4	45.4	48.8	46.4
King Site Index (m)					
Mean	50.3	45.2	37.7	38.0	45.4
Std. Dev.	11.8	11.7	7.3	5.7	8.9
Coef. Var.	23.4	25.8	19.4	14.9	19.6
Minimum	1.4	1.4	9.6	25.1	31.0
Maximum	80.4	77.2	61.8	63.2	59.6

Chapter 5: Epilogue

5.1 Background

The purpose of this thesis was to document selected portions of the Coast Range RVMM modeling project for which I (i) shared responsibility (development of a database for long-term growth and yield modeling), (ii) developed static tree-level prediction equations for attributes sampled during data collection, and (iii) developed a site productivity index for young Douglas-fir stands.

5.2 Database

The development of the Coast Range RVMM database was described with respect to its underlying design matrix, sampling and data collection protocols, extent and location of established growth monitoring plots, and representative tree and associated vegetation attributes. The design matrix and sampling and data collection protocols were the basis for the installation of 98 growth monitoring plots in the Coast Range Mountains of Oregon and Washington.

The utility of the database was demonstrated by the subsequent development of the Coastal RVMM, a 'front-end' young-stand growth model (inclusive of associated vegetation competition effects) for existing rotation-age growth models (e.g., ORGANON, Hann et al., 1995). The potential exists to remeasure the permanent growth monitoring plots in the future, and to thereby, extend the database and enable further tree and associated vegetation growth analyses.

5.3 Static Tree-Level Equations

The development of static tree-level equations to predict a number of tree-level attributes that were sub-sampled during data collection was presented. The basic form of the equations have a foundation in current biometric literature, although each were uniquely adapted to accommodate available independent variables or to be applied more generally. Thirty-six prediction equations were developed for Douglas-fir, 3 other conifers, and 6 hardwood species for the attributes: single-stem diameter, multi-stem basal area, total tree height, crown width, and a dbh-d15 relationship.

The utility of the prediction equations is demonstrated by the completion of the Coastal RVMM database, which facilitated a full accounting of per hectare sums and means of relevant stand-level attributes for use in growth analyses. These prediction equations are available for similar utility in future tree growth analyses by interested researchers.

5.4 Juvenile-Stand Height Potential Index

The development of a Douglas-fir juvenile-stand height potential index (HPI) was described. To develop the index, the young-stand Coastal RVMM dataset was augmented with four other datasets to extend the breadth of the overall database with regard to stand age and site quality. The juvenile-stand height potential index equation is an algebraic-difference formulation of an exponentiated and generalized Schumacher growth equation. Recommended base-age is 20 years breast-height-age, although the equation is base-age invariant. In comparison with existing site-index equations, HPI represents greater dominant height growth to about breast-height age 20 years. For older plantations, HPI underestimates site-height potential relative to existing site-index equations, although HPI is predicted much more consistently across the entire breast-height-age range in the developmental database.

The utility of the HPI was demonstrated by the provision of juvenile-stand height index determined from Coastal RVMM for subsequent use in rotation-age growth models, and to provide an explanatory variable for the prediction of individual-tree growth. The potential exists for future work to locate and incorporate additional datasets, including 'free-to-grow' or 'bare ground' growing conditions, and thereby, extend the database to enable an iterative analyses of dominant height-growth (with and without entirely 'free-to-grow' conditions).

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APPENDICES

Appendix 1: Species List and Code

Conifer Species	Garrison Code (Garrison and Skovlin, 1976)
Douglas-fir	
(*Pseudotsuga menziesii* [Mirb.] Franco)	PSME
Sitka spruce	
(*Picea sitchensis* [Bong.] Carr.)	PISI
western hemlock	
(*Tsuga heterophylla* [Raf.] Sarg.)	TSHE

Hardwood species	
red alder	
(*Alnus rubra* Bong.)	ALRU
vine maple	
(*Acer circinatum* Pursh.)	ACCI
bitter cherry	
(*Prunus emarginata* [Doug.] Walp.)	PREM
hazel	
(*Corylus comuta* Marsh.)	COCO
cascara	
(*Rhamnus purshiana* DC.)	RHPU
chinquapin	
(*Castanopsis chrysophyla* [Doug.] DC.)	CACH
bigleaf maple	
(*Acer macrophyllum* Pursh.)	ACMA
willow	
(Salix spp.)	SALI
hardwoods, generic	HDWD

Appendix 1, continued: Species List and Code

Herbaceous species	Garrison Code (Garrison and Skovlin, 1976)
bracken fern	
(*Pteridium aquilinum* [L.] Kuhn.)	PTAQ
swordfern	
(*Polystichum munitum* Kaulf.)	POMU
thistle	
(*Cirsium* spp. L)	CISP
willow-herb	
(*Epilobium* spp. L.)	EPSP
Shrub species	
Oregon grape	
(*Berberis nervosa* Pursh.)	BENE
Salmonberry	
(*Rubus spectabilis* Pursh.)	RUSP
salal	
(*Gaultheria shallon* Pursh.)	GASH
rhododendron	
(*Rhododendron macrophyllum* G. Don)	RHMA
huckleberry	
(*Vaccinium* spp. L.)	VASP
buckthorn	
(*Ceanothus* spp. L.)	CESP

Appendix 2: Static Diameter Equation Statistics for (a) d15 and (b) dbh Trees

(a) Basal diameter (mm) at 15 cm above the ground

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient[3]		
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2
PREM	10	134	Ht-15 Cw	2.40	0.62	0.59	2.24	$(Ht-15)^{-1}$	16.5599	-2.4798	-0.0104
RHPU	7	38	Ht-15 Cw	1.43	0.76	0.75	1.32	$(Ht-15)^{-1}$	0.9452*	0.3939	0.0870
SALI	7	24	Ht-15 Cw	2.09	0.47	0.46	1.99	$(Ht-15)^{-1}$	1.1954*	0.3180*	0.1267*
TSHE	9	29	Ht-15	4.35	0.52	0.52	3.73	Ht^{-1}	2.5377	0.0163	-
PSME	8	894	Ht-15 z^2	3.29	0.77	0.77	2.93	Ht^{-1}	0.4169	0.8406	-0.0515

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations
1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted
   * RHPU: a0 significantly different than 1 (SD_1) at 28%
   * SALI: a0 significantly different from 0 and 1 (SD_{01}) at 88% and 20%, respectively
     a1 SD_0 at 94%
     a2 SD_0 at 92%
2. z = 0 for a planted tree; z = 1 for a wildling tree

Appendix 2, continued: Static Diameter Equation Statistics for (a) d15 and (b) dbh Trees

(b) Diameter breast-height (mm) at 137 cm above the ground

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient[3]		
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2
PREM	7	121	Ht-137 Cw	4.75	0.93	0.93	2.79	$(Ht-137)^{-1}$	0.3227	0.4968	0.0827

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations

1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted.

Appendix 3: Static Equation Statistics for Multi-Stem Rootstock Basal Area for (a) d15 and (b) dbh Trees

(a) Basal area (10^{-4} m^2) at 15 cm above the ground

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient		
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2
ACCI	10	46	Ht-15 Cw	1.73	0.54	0.53	1.37	$pred^{-1}$	5.7861	-4.1466	-0.0070

(b) Basal area (10^{-4} m^2) at 137 cm above the ground

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient[3]		
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2
ACCI	10	135	Ht-137 Cw	7.40	0.59	0.56	5.52	$pred^{-1}$	39.9149	-5.5190	-0.0014
COCO	10	93	Ht-137 Cw	2.09	0.92	0.92	1.56	$pred^{-1}$	150.5671	-5.8430	-0.0005
RHPU	10	34	Ht-137 Cw	13.32	0.83	0.81	5.61	$pred^{-1}$	261.8416	-6.2814	-0.0007

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations

1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation

Appendix 4: Static Height Equation Statistics for Trees < Breast-Height

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient[3]		
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2
ACCI[4]	1a	87	d15	17.87	0.57	0.57	17.95	$pred^{-1}$	-0.1206	1.5845*	-
PREM	1a	95	d15	17.84	0.63	0.61	15.84	$d15^{-1}$	-0.1429	1.4472	-
RHPU	1a	56	d15	15.39	0.77	0.76	14.95	$pred^{-1}$	-0.2136	2.8978	-
TSHE	1a	29	d15	15.34	0.79	0.78	14.36	$d15^{-1}$	-0.1993	2.1245	-
PSME	1b	894	d15 z[5]	14.68	0.80	0.80	14.23	$pred^{-1}$	-0.0993	1.7788	-0.4603

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations

1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted
   * ACCI: a1 significantly different than 1 (SD_1) at 90%
4. Coefficients are from the unweighted regression
5. z = 0 for a planted tree; else, z = 1 for a wildling tree

Appendix 5: Static Height Equation Statistics for Trees > Breast-Height

Species	Eq. No.[1]	n	x1	Unweighted Regression		Weighted Regression			Coefficient[3]			
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2	a3
ACCI	4a	185	dbh	75.82	0.72	0.72	67.19	dbh^{-1}	7.3113	10.8068	-0.5901	-
ALRU	4a	259	dbh	138.11	0.84	0.83	128.52	dbh^{-1}	7.8980	10.4858	-0.4955	-
PISI	4a	34	dbh	89.00	0.83	0.83	84.94	dbh^{-1}	8.5978	-9.5349	-0.3430*	-
PREM	4a	130	dbh	67.24	0.92	0.92	41.84	dbh^{-1}	8.6885	-8.2191	-0.3363	-
RHPU	4a	85	dbh	88.27	0.88	0.87	70.42	dbh^{-1}	7.7234	10.6843	-0.5375	-
TSHE	4a	306	dbh	122.30	0.87	0.87	106.55	dbh^{-1}	8.9665	-8.1739	-0.2684	-

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations
1. Equation numbers as referenced in the text
2. x1 is the explanatory variable in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted
   * PISI: a2 significantly different than 0 (SD_0) at 62%

Appendix 5, Continued: Static Height Equation Statistics for Trees > Breast-Height

Spp.	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient[3]			
				Furn. Index	R^2	R^2	Furn. Index	Wt.	a0	a1	a2	a3
AL	4a	253	dbh Cw	125.14	0.86	0.86	115.86	dbh^{-1}	9.6179	-9.8166	-0.3000	0.0008
CO	4c	101	dbh Cw	55.20	0.75	0.75	44.56	dbh^{-1}	2.1169	0.6476	-0.1332	-
RH	4a	79	dbh Cw	89.26	0.88	0.87	75.80	$pred^{-1}$	10.6703	10.6033	-0.2536	0.0010
PS	4b	5022	dbh z[4]	115.26	0.91	0.91	90.73	dbh^{-1}	9.6858	11.1810	-0.2731	0.0122

Note: Species codes are defined below and in Appendix 1; other abbreviations are defined in the List of Abbreviations
AL=ALRU; CO=COCO; RH=RHPU; PS=PSME

1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted
4. z = 0 = planted tree; else, z = 1 = wildling tree

Appendix 6: Static Crown Width Equation Statistics for Trees < Breast-Height

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient [3]		
				Furnival Index	R^2	R^2	Furnival Index	Weight	a0	a1	a2
ACCI	11	136	d15 nstem	20.53	0.81	0.81	19.16	$pred^{-1}$	7.1517	0.6811	0.3416
RHPU	11	78	d15 nstem	12.74	0.60	0.59	12.41	$d15^{-1}$	5.0431	0.7965*	0.2060
PSME	7	820	ht d15	11.44	0.86	0.86	10.43	ht^{-1}	3.1893	0.4007	0.1467

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations

1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted
   * RHPU: a1 significantly different than 1 (SD_1) at 93%

Appendix 7: Static Crown Width Equation Statistics for Trees > Breast-Height

Species	Eq. No.[1]	n	x1 x2[2]	Unweighted Regression		Weighted Regression			Coefficient [3]		
				Furn. Index	R^2	R^2	Furn. Index	Wt.	a0	a1	a2
ACCI	11	176	dbh nstems	57.78	0.60	0.59	54.81	dbh^{-1}	35.6591	0.4381	0.2183
ALRU	5	329	dbh	81.53	0.70	0.69	78.21	$pred^{-1}$	19.6323	0.6542	-
PISI	5	64	dbh	29.05	0.79	0.79	28.09	$pred^{-1}$	23.6442	0.5197	-
TSHE[4]	5	330	dbh	50.15	0.90	0.89	51.31	$pred^{-1}$	18.3211	0.6254	-
PSME	8	3982	dbh z[5]	49.58	0.90	0.90	45.33	$pred^{-1}$	21.9132	0.6072	-0.0183

Note: Species codes are defined in Appendix 1; other abbreviations are defined in the List of Abbreviations

1. Equation numbers as referenced in the text
2. x1 and x2 are the explanatory variables in the equation
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else otherwise noted
4. Coefficients are from the unweighted regression
5. z = 0 for a planted tree; else, z = 1 for a wildling tree

Appendix 8: Static Dbh-D15 Equation Statistics for 15 < Tree Height ≤ 300 Centimeters

Spp.	Eq. No.[1]	n	x1 x2 x3[2]	Unweighted Regression		Weighted Regression			Coefficient [3]			
				Furn. Index	R^2	R^2	Furn. Index	Wt.	a0	a1	a2	a3
									a4	a5	a6	-
HD	12	176	d15 Ht spp[2]	1.79	0.74	0.74	1.74	$pred^{-1}$	15.1554	-4.3870	-0.0024	9.8178
									4.5058*	5.5464	10.0033	-
TS	10	24	d15 Ht	1.57	0.82	0.82	1.51	$d15^{-1}$	17.1256	-9.7197	-0.0040	-
PS	13	367	d15 Ht z[4]	1.97	0.89	0.89	1.78	$pred^{-1}$	36.9485	-6.2501	-0.0024	2.9045

Note: Species codes are defined below and in Appendix 1; other abbreviations are defined in the List of Abbreviations
HD=HDWD; TS=TSHE; PS=PSME
1. Equation numbers as referenced in the text
2. x1 and x2 and x3 are the explanatory variables in the equation (x3=RHPU, x4=PREM, x5=COCO, x6=ACCI)
3. Coefficients significantly different than 0 and 1 at ≥ 95%, else PREM: a4 SD_{01} at 93% and 84%, respectively
4. z = 0 for a planted tree; else, z = 1 for a wildling tree