Stand-Level Scaling of a Single-Tree, Distance-Independent, Diameter-Growth Model: Interim Calibration of Prognosis for the Southeastern Interior of British Columbia

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Abstract—The main feature of the 1998 release of Prognosis^{BC} is an interim calibration of its large-tree diameter-growth model. The calibration is based on the development of multiplier functions that predict the ratio between growth rates inherent in the northern Idaho variant of the Prognosis Model (now called the Forest Vegetation Simulator in the United States) and those rates observed in long-term permanent sample plots (PSP) in the Nelson, Kamloops and Cariboo forest regions of British Columbia, Canada. The self-calibration feature of the Prognosis Model was used to generate the calibration statistics. These statistics were then modelled as a function of variables whose effects were hypothesized to change as the model range is expanded northward. This paper discusses the methodology and presents the results of this stand-level calibration of an individual-tree, diameter-growth model.

The Forest Vegetation Simulator (FVS) (Stage 1973; Wykoff and others 1982) — FVS is a new name for the Prognosis Model — is a single-tree, distance-independent model of forest-stand dynamics. The model also provides linkage to other submodels of various components of the ecosystem such as root disease and understory development. The architecture of the model is such that the model is applicable to a wide range of timber types and stand conditions. During execution of the model, growth measured in the current inventory can be used to scale its projections, providing a smooth link between past experience and the future projections. This feature also provides a convenient means to extend the range of model applicability.

The British Columbia (B.C.) Ministry of Forests in Canada is currently adapting the northern Idaho (NI) variant of FVS to the Southeastern Interior of British Columbia. This variant of the model was selected as a basis because of its geographic proximity and its use of classes of potential vegetation or habitat types (Daubenmire and Daubenmire 1968) as part of its index of productivity.

An initial approach to extending the model northward was to map the B.C. Biogeoclimatic Ecosystem Classification (BEC) classes (Meidinger and Pojar 1991) onto the Daubenmire habitat types represented in the northern Idaho variant (McKenzie 1991; Sargent and McKenzie 1997).

BEC units represent groups of ecosystems under the influence of the same regional climate. Zones are divided into subzones (actually the subzones are the basic units and aggregate to zones). The notation used is ZONEab, where ZONE is abbreviation of the zone (ICH, IDF...and so forth) and "a" and "b" are two letters that define the subzone based on precipitation and temperature, respectively. The codes for "a" could be x (very dry), d (dry), m (moist), w (wet), or v (very wet). The codes for "b" could be h (hot), w (warm), m(mild), k (cool), c (cold), and v (very cold). A subzone may further be divided into variants (a geographic location identifier) indicated by a number that follows the zone and subzone, for example, ICHmw2 (the Schuswap moist warm Interior Cedar-Hemlock variant). A subzone or variant is divided into Site Series (01, 02…and so forth). Site Series group ecosystems within a subzone or variant by environmental properties (soil moisture and nutrient regimes) and potential climax vegetation. The 01 is the zonal (typical) series of the variant. Site Series with numbers less than 4 (for example, 02 and 03) are (generally) drier and poorer. Site Series with numbers greater than or equal to 4 (04, 05,06…and so forth) generally occur on wetter, richer sites. However, the soil moisture or nutrient regime of a given series relative to the zonal (01) may vary from variant to variant.

The prevailing BEC zones in Southeastern B.C. that were included in this study are the Engelmann Spruce-Subalpine Fir (ESSF), the Interior Cedar Hemlock (ICH), the Interior Douglas-fir (IDF), the Montane Spruce (MS), and the Ponderosa Pine (PP). This approach of mapping the BEC units to habitat types permitted B.C. analysts to evaluate the potential usefulness of the Prognosis architecture in their decisionmaking context.

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The longer term objective is to have a variant of Prognosis for Interior British Columbia that is based entirely on local data. However, that objective may require more specific data than are presently available. In the interim, useful projections seem possible with a model that uses our limited B.C. data to adjust for the major ecological differences between northern Idaho and Southeastern B.C. This adaptation consists of a series of steps, ordered by the sensitivity of the model to our ecological differences. Each step provides an interim model with improved representation of B.C. forests:

1. Convert the NI variant from Imperial units to metric units of measure including the B.C. static tree-volume equations (Robinson 1997).
2. Modify the large-tree diameter-increment component to recognize BEC classes, and determine appropriate scaling factors using diameter-increment data from B.C. permanent sample plots (PSP's). The methods used in this step are the primary feature of this report and are the basis for the 1998 release of Prognosis^{BC}.
3. Modify the individual-tree mortality model to agree with B.C. PSP data.
4. Modify the large-tree height-increment model to use the BEC classes in place of NI habitat types.
5. Construct a height-increment submodel for small trees (less than 12.5cm.).
6. Construct a submodel for regeneration.

Steps 3, 4, 5, and 6 are in process and are expected to form the basis for a future release of Prognosis^{BC} in early 2002. Calibration of the diameter-increment submodel was the first step in modifying the dynamic (growth and mortality) aspects of the northern Idaho variant. This paper presents the interim calibration of the diameter-increment submodel for the Southern Interior of British Columbia.

Background

In the northern Idaho (NI) variant of the Forest Vegetation Simulator (FVS), the overall model behavior is sensitive to the diameter-growth component for trees larger than 12.5 cm. This sensitivity is a consequence of the model's use of diameter at breast height (d.b.h.) and diameter increment in the prediction of changes in other tree attributes (height growth, mortality, and crown length). The NI variant of Prognosis is thus predominantly a diameter-driven growth-and-yield model as opposed to height-driven models that use a potential height-growth based on site index. Therefore, we started the calibration of FVS to the Southern Interior of British Columbia with the diameter-increment model. The diameter-increment model predicts 10-year diameter increment in trees greater than 12.5 cm in d.b.h. The model uses tree and stand attributes, site and location variables to predict the change in inside-bark d.b.h. The model modifies this prediction for trees less than 25 cm to provide a smooth transition between the large-tree estimates and the diameter-increment estimates derived from height increment for trees less than 12.5 cm.

The form of the diameter-increment model (Wykoff 1986) is as follows:

$$Ln(DDS) = HAB + LOC + b_1*SL*\cos(ASP) + b_2*SL*\sin(ASP) + b_3*SL + b_4*SL^2 + b_5*EL + b_6*EL^2 + b_7*\ln(DBH) + b_8*CR + b_9*CR^2 + b_{10}*(BAL/100) + b_{11}*BAL/(DBH+1) + b_{12}*DBH^2 + b_{13}*(CCF/100) \quad \text{(Eq. 1)}$$

Where:

Ln(DDS) = Natural log of 10-year change in squared inside-bark diameter
HAB = Constant term that is dependent on habitat type
LOC = Constant term that is dependent on location
SL = Stand slope ratio
ASP = Stand aspect (degrees)
EL = Stand elevation (hundreds of feet)
CCF = Stand crown competition factor
CR = ratio of crown length to total tree height
DBH = diameter at breast height
BAL = Stand basal area in trees larger than the subject tree
b_1,.., b_{13} = Species-specific regression coefficients

The regression coefficients in the NI variant of FVS, at the time the model was adopted for calibration in B.C., were given in Wykoff (1986).

Data

Permanent sample plots (PSP) have been established throughout the operable land base in B.C. (B.C. Forest Productivity Council Minimum Standards Manual 1995). The PSPs used in the calibration were selected from the Nelson, Kamloops, and the Cariboo forest regions based on the following criteria:

- The PSP has been measured at least twice.
- The plot has been ecologically classified to the site series using the Biogeoclimatic Ecological Classification system.
- The plot Biogeoclimatic Ecological Classification at the site-series level has been mapped to a corresponding northern Idaho habitat type.
- Measurement periods were excluded if the plots were disturbed or partially cut between any successive measurements.
- Only measurement periods of 9, 10, or 11 years were selected. This was intended to minimize the effects of interpolating to a 10-year growth cycle.

Repeated measurements on the selected plots were used to provide the initial tree and stand conditions and a 10-year diameter increment. The distribution of PSP data used in the interim calibration by forest region is given in tables 1 and 2.

In addition to the tree-list data, a keyword list was also prepared for each sample plot. The tree list and keyword list were used to project the stand between successive measurements. For the purpose of these calibration projections, the plot elevation, slope and aspect were set to the average conditions in the northern Idaho data used to develop the variant. This substitution results in a reduced model where the aspect, slope and elevation terms become part of the model constant terms (equation 1).

The plot site series from the British Columbia Biogeoclimatic Ecological Classification (BEC) were mapped to nearest corresponding NI habitat type. The mapping of the BEC site series in the Nelson and Kamloops forest

Table 1—PSP distribution by BEC site series, number of plots and average number of trees in the plot in the Kamloops and Cariboo forest region.

	Site series				
Subzone/variant	**03**	**04**	**01**	**05**	**06**
ICHmk1	7 (65)	4 (42)			
ICHmw2	n/m	1 (14)	47 (43)	2 (21)	
ICHmw3	No Data	n/m	24 (40)		
IDFdk1	n/m	17 (53)	18 (53)		
IDFdk2	20 (50)	n/m	37 (66)		
IDFdk3	n/m	6 (54)	32 (53)	n/m	11 (49)
IDFdm1	n/m	2 (55)	1 (24)		
IDFmw1	n/m	3 (62)			
IDFxh1	n/m	2 (53)	8 (63)		
IDFxh2	n/m	n/m	n/m	4 (74)	2 (78)
MSdm1	n/f	5 (27)			
PPxh2	3 (27)				

n/m = Site series not mapped to a corresponding habitat type.
n/f = Site series not forested

Table 2—PSP distribution by BEC site series, number of plots and average number of trees in the plot in the Nelson forest region.

	Site series					
Subzone/variant	**02**	**03**	**04**	**01**	**05**	**07**
ESSFdk	n/m	n/m	9 (48)	11 (29)		
ESSFwc4	4 (49)	3 (78)	n/m	n/m		
ESSFwm	No Data	3 (38)	1 (29)	9 (29)		
ICHdw	n/m	n/m	No Data	45 (44)		
ICHmk1	n/m	30 (57)	15 (55)	25 (71)	2 (65)	
ICHmw1	n/m	n/m	n/m	1 (110)		
ICHmw2	n/f	82 (61)	69 (41)	22 (36)	2 (45)	
ICHmw3	n/m	2 (43)	6 (26)	6 (25)	8 (30)	1 (26)
ICHwk1	n/f	n/m	1 (31)	No Data		
IDFdm1	n/f	n/m	12 (32)	25 (30)		
IDFdm2	n/f	n/m	13 (48)	43 (62)		
MSdk	n/f	5 (51)	49 (83)	15 (43)		
MSdm1	No Data	No Data	2 (23)	No Data		
PPdh2	n/f	n/m	n/m	5 (59)		

n/m = Site series not mapped to a corresponding habitat type.
n/f = Site series not forested.

regions of B.C. to the corresponding northern Idaho habitat types is given in tables 3 and 4. The tables show the habitat-type codes used in FVS. For more details on the habitat types represented by these codes, see Wykoff and others (1982).

Calibration Statistics

Wykoff and others (1982) gave a brief description of the FVS model selfcalibration process. The calibration process scales growth predictions of each species to match the input growth data from the PSP repeated measures. Calibration statistics represent the magnitude of the scaling factor needed such that the plot totals of the model-based growth estimates will equal the totals as measured on the plot. The adjustment includes an empirical-Bayes-based averaging of the estimates from the a priori, imbedded-increment model and the a posteriori stand sample of increments. The version of FVS used in this study reports the unadjusted values of the calibration statistics. Newer versions of FVS now report the modified calibration statistics.

The diameter-increment scale factors are expressed as a multiplier to the change in squared diameter and are in effect multipliers of the tree-basal-area increment. The calibration statistics were computed for each projected-growth-measurement period.

Table 3—Mapping of the BEC site series to habitat types in the Nelson forest region.

	Site series					
Subzone/variant	**03**	**04**	**01**	**05**	**05**	**07**
			FVS Habitat Type Codes			
PPdh1			PIPO/AGSP			
PPdh2			PIPO/AGSP			
IDFdm1		PSME/CARU	PSME/VACA	ABLA/VACA		
IDFdm2			PSME/VACA			
IDFxh1		PSME/CARU	PSME/CARU			PSME/SYAL
ICHdw		THPL/OPHO	TSHE/CLUN			
ICHmw2		TSHE/CLUN	TSHE/CLUN	THPL/OPHO	THPL/OPHO	
ICHmw3	PSME/VACA		TSHE/CLUN			THPL/OPHO
ICHmk1	PSME/VACA	ABLA/VACA				
ICHwk1				THPL/OPHO		
ICHvk1			THPL/OPHO			
MSdm1		PSME/VACA				
ESSFdc1	ABLA/VASC					

Table 4—Mapping of the BEC site series to habitat types in the Kamloops forest region.

	Site series					
Subzone/variant	**03**	**04**	**01**	**05**	**05**	**07**
			FVS Habitat Type Codes			
PPxh1		PIPO/AGSP	PIPO/AGSP		PSME/SYAL	PSME/SYAL
PPxh2	PIPO/AGSP					
IDFxh1		PSME/CARU	PSME/CARU			
IDFxh2				PSME/CARU	PSME/CARU	
IDFdk1		PSME/CARU	PSME/CARU			
IDFdk2	PSME/CARU		PSME/VACA			
IDFdk3			PSME/CARU			
IDFdm1		PSME/CARU	PSME/CARU	THPL/ATFI		
IDFmw1		PSME/VACA				
ICHmw2		TSHE/CLUN	TSHE/CLUN	THPL/OPHO	THPL/OPHO	
ICHmw3	PSME/VACA		TSHE/CLUN			THPL/OPHO
ICHwk1				THPL/OPHO		
ICHmk1	PSME/VACA	ABLA/VACA				
ICHvk1			THPL/OPHO			
MSdm1		PSME/VACA				
Msxk				PSME/CARU		
ESSFdc1	ABLA/VASC					

Calibration Methods

The next step models the calibration statistics obtained for each plot. Effects of stand elevation, slope, and aspect on tree growth are expected to change as the model's geographical scope is expanded northward. Setting the plot elevation, aspect, and slope to the average NI conditions during the calibration runs allowed us to examine the correlation between the model-generated calibration statistics and the actual elevation, aspect, and slope of the plot. The stand stocking, expressed as CCF, was also chosen as a potential predictor variable. The inclusion of CCF in a regression model to predict plot-level calibration statistics provides a stand-level adjustment to the species-specific CCF regression coefficients in the original NI model.

Mapping of the BEC units to corresponding NI habitat types was not a one-to-one mapping. It was a subjective process based on the ecologist's best knowledge of the vegetation characteristics of the BEC unit and the habitat type. Differences between the two systems of classification could result in more than one habitat type as a possible match to a given BEC site series (McKenzie 1991; Sargent and McKenzie 1997), so that two or more site series are mapped to the same habitat type. The inclusion of the BEC site series as a predictor variable is expected to explain that source of variation in the calibration statistics that may be due to differences between a BEC site series and the habitat type to which it had been mapped.

The regression model of plot-level FVS-generated calibration statistics as a function of stand aspect, slope, elevation, BEC site series, and CCF is:

$$\text{Ln (Scale)} = \text{SITE} + c_1*\text{SL}*\sin(\text{ASP}) + c_2*\text{SL}*\cos(\text{ASP}) + c_3*\text{SL} + c_4*\text{EL} + c_5*\text{EL}^2 + c_6*(\text{CCF}/100) \quad \text{(Eq 2)}$$

Where:

Scale = Prognosis-generated plot-level scale factor for 10-year change in squared diameter

SITE = Constant term that is dependent on the BEC site series

C_1 to C_6 are species-specific regression coefficients.

All other variables appear in equation (1) and are defined there.

The natural-log transformation of the dependent variable was selected to have a model that is consistent with the original NI model (equation 1). The growth multiplier becomes an additive term on the log scale. In this formulation, the CCF coefficient C_6 in equation (2) becomes a stand level adjustment to the original CCF term (b_{13}) of equation (1). The aspect, slope and elevation terms with coefficients C_1 to C_5 in equation (2) are in effect adjustments to the constant term that resulted from the use of the average NI aspect, slope, and elevation conditions in the model runs that generated the scale factors. The model in equation (2) was fit to each of 10 coniferous species included in the original model. Of the 11 species covered in the NI version, only mountain hemlock was not included in the analysis due to lack of PSP data. A list of the tree species included in the analysis is given in table 5.

Results and Discussion

The fit statistics for equation (2) are shown in table 6. The adjusted R^2 values ranged from 0.10 for hemlock and western white pine to 0.56 for subalpine fir. Note that low R^2 values indicate species for which the NI model required little change. Standard errors of the estimate ranged from 0.29 to 0.46 on the log scale. For Douglas-fir, for example, the standard error on the log scale is 0.36, which results in a lower and upper one-standard deviation of 0.70 and 1.43, respectively, or 30 and 43 percent error.

Table 5—Tree species included in the large-tree diameter-growth model calibration.

Common name	Code	Scientific name
Western white pine	Pw	*Pinus monticola*
Western larch	Lw	*Larix occidentalis*
Douglas-fir	Fd	*Pseudotsuga menziesii*
Western hemlock	Hw	*Tsuga heterophylla*
Western redcedar	Cw	*Thuja plicata*
Lodgepole pine	Pl	*Pinus contorta*
Engelmann spruce	Se	*Picea engelmannii*
Grand fir	Bg	*Abies grandis*
Subalpine fir	Bl	*Abies lasiocarpa*
Ponderosa pine	Pp	*Pinus ponderosa*

Table 6—Fit statistics for equation (2).

Species	No. of plots (N)	Adjusted R^2	Standard error of estimate
Douglas-fir	1130	0.20	0.3562
Lodgepole pine	779	0.26	0.2995
Western larch	592	0.20	0.4614
Western redcedar	541	0.14	0.4033
Western hemlock	368	0.10	0.3509
Western white pine	209	0.10	0.3616
Engelmann spruce	167	0.20	0.4033
Subalpine fir/Grand fir	73	0.56	0.3779
Ponderosa pine	58	0.38	0.4441

Least squares estimates of the regression coefficients of equation (2) are presented in tables 7 and 8. The negative significant CCF coefficients (C_6) for Douglas-fir and lodgepole pine indicate that the two species are more negatively affected by stand density in Southeastern B.C. than in the northern Idaho variant of Prognosis. The positive effect of elevation on growth is offset by a significant EL^2 term for the species that occur in a wide range of elevation, indicating that an optimum elevation does exist for these species. The magnitude of the EL^2 coefficient is higher for the two species that occur mostly in the higher elevations of the Englemann Spruce Subalpine Fir (ESSF) zone, namely spruce and subalpine fir. For all other species, C_5 of equation (2) is not significantly different from zero.

Constant terms for site series are given in table 7. These coefficients represent site differences as well as an adjustment for any possible mapping mismatch between the site series and the NI habitat type deemed most appropriate. Because of this confounding effect, the coefficients for a given species cannot be interpreted to indicate site differences between the different site series for that species. We could add the intercept given for the root habitat type to the new intercept for each BEC class. However, as the intercept also includes the mean times regression coefficient for each of the other variables in the model, its interpretation as relative productivity is still clouded.

For each species, residual analysis by BEC site series showed that there were no significant biases in the predicted scale factors across the site series.

The large-tree diameter-growth model implemented in the current release of Prognosis^{BC} is a combination of equation (1), in which aspect slope and elevation were fixed to the average of these conditions in NI, and equation (2). Preliminary verifications of the model's performance (Temesgen and Lemay 1999) indicated no serious bias in the overall behavior of the model. Furthermore, and because diameter growth is an important predictor of height growth, Temesgen and LeMay (1999) found that the large-tree height model performed well in the site series where the diameter model was calibrated.

Table 7—Species-specific coefficients in the calibration function for the large-tree, diameter-increment model (equation 2).

Variable	Species	PW	LW	FD	HW	CW	PL	SE	BL/BG	PY
Overall constant		–1.20012	0.03164	–0.33768	–0.53158	0.30382	–0.57696	–1.46710	–0.65511	–2.01572
Sl.Cos(ASP)	C1			0.00083			–0.08531			–1.11471
SL.Sin(ASP)	C2								–0.74662	
SL	C3							–0.82000		
EL	C4	0.01724		0.01048	0.04685		0.01065	0.07223	0.07129	0.06151
EL^2	C5				–0.00068			–0.00090	–0.00099	
CCF	C6			–0.07463			–0.16348			

Table 8—Species-specific, BEC constant terms in the calibration function for the large-tree, diameter-increment model (equation 2). The shaded cell(s) indicate the site series or group of site series for which the constant term applies.

BEC variant	Site series 2	Constant
Western white pine		
ICH		0.97080
mw2		0.55088
mw3		0.54472
		1.57930
Western larch		
ICH		—0.24679
		—0.11546
mk1		—0.45001
IDF		0.16060
dm2		—0.53506
		—0.83091
mw1		—0.28032
MS		—0.47719
		—0.13477
Douglas-fir		
ICH		0.22398
mk1		0.15358
mw2		0.26506
		0.12485
mw3		0.52539
		0.37126
		0.16271
wk1		0.29088
IDF		0.13588
dk2		0.28110
dk3		—0.17949
		—0.73119
		—0.18901
dm1		0.31994
		0.11163
dm2		0.14139
mw1		0.35498
xh1		—0.20460
xh2		
MS		0.22099
Grand fir		
ESSF		—0.68074
wm1		0.26881
ICH		—1.32980
mk1		—0.99113
mw2		—1.08111
mw3		—0.74432
MS		—0.49646
Western hemlock		
		—0.33966
		—0.32891
		—0.38468
		—0.35852
		—0.34059
		—0.33842
Western redcedar		
		—0.67998
		—0.53091
		—0.24884
		—0.45763
mw3		—0.94850
		—0.26425
		—0.36550
		—0.74451
		—0.50328
		—0.85966
		—0.93040
Lodgepole pine		
		0.14517
		0.21038
		0.10317
		0.24878
		—0.29809
		—0.44302
		—0.53275
		—0.38840
		—0.31680
Engelmann spruce		
		0.26510
		0.72027
		0.30629
mk1		—0.21132
Subalpine fir		
		—0.68074
		0.26881
ICH		—1.32980
		—0.99113
mw2		—1.08110
mw3		—0.77432
		—0.49646
Ponderosa pine		
IDF		—0.44823
xh1		—0.41938
xh2		—0.68892

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