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Forest Vegetation Simulator Model Calibration for Ontario (FVS$^{\text{Ontario}}$)

Project number 130-107

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Information Report LAU-X-132
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LIBRARY AND ARCHIVES CANADA CATALOGUING IN PUBLICATION

Forest Vegetation Simulator model calibration for Ontario (FVS^{Ontario})
[electronic resource] / V. Lacerte… [et al.].

(Information report, 0835-1570; LAU-X-132)
Electronic monograph in PDF format.
Mode of access: World Wide Web.
Issued also in French under title: Calibration du modèle de simulation
"Forest Vegetation Simulator" (FVS^{Ontario}) pour l'Ontario.
ISBN 978-0-662-47340-4
Cat. no.: Fo113-3/132E-PDF

1. FVS Ontario (Computer file).
2. Trees – Growth – Measurement.
3. Trees – Growth – Computer simulation.
4. Forests and forestry – Measurement.
5. Forests and forestry – Computer simulation.
6. Forest management – Ontario.
7. Forest ecology – Ontario.
I. Lacerte, V. (Valérie)
II. Laurentian Forestry Centre
III. Series: Information report (Laurentian Forestry Centre: Online); LAU-X-132

SD555.V3414 2008 634.9'285 C2007-980269-9

Catalog Number Fo113-3/132E-PDF
ISBN 978-0-662-47340-4
ISSN 0835-1570

This publication is available in PDF at no charge from the Canadian Forest Service Bookstore at:
http://bookstore.cfs.nrcan.gc.ca

TTY: (613) 996-4397 (teletype for the hearing impaired)

Cette publication est également offerte en français sous le titre « Calibration du modèle de simulation « Forest Vegetation Simulator » (FVS^{Ontario}) pour l'Ontario » (numéro de catalogue Fo113-3/132F-PDF).

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ABSTRACT

The FVS^{Ontario} (Forest Vegetation Simulator) model, which originated from the Lake States-TWIGS geographic variant of FVS, was calibrated for 19 species of the boreal and Great Lakes–St. Lawrence forest regions of Ontario. New growth and yield models were derived using data from permanent sample plots located in these regions. The new models were derived for the following dependent variables: dbh (diameter at breast height) growth rate, survival rate, stem height and species group density index (SGDI) for large trees (7.5 cm and greater in dbh), and height and dbh growth rate for small trees (less than 7.5 cm in dbh). The mean residuals of the new FVS^{Ontario} models were smaller than the mean residuals of the original Lake States-TWIGS models, which indicated that the new models better represented the regional variation in site index, stand density and age for most species. Furthermore, an analysis of biological consistency indicated that all the dependent variables changed logically with changes in site index, stand density, basal area or age.

RÉSUMÉ

Le modèle de simulation « Forest Vegetation Simulator » ou FVS^{Ontario}, issu de la variante géographique LS-TWIGS de FVS, a été calibré pour 19 espèces de la région forestière boréale et de la région des Grands Lacs–Saint-Laurent en Ontario. De nouveaux modèles de croissance et de rendement ont été élaborés à partir des données de placettes-échantillons permanentes situées dans ces régions. Ces nouveaux modèles ont été créés pour les variables dépendantes suivantes : taux de croissance en dhp (diamètre à hauteur de poitrine), taux de survie, hauteur des tiges en fonction du dhp et indice de densité de groupe d’espèces (IDGE) pour les grands arbres (7,5 cm et plus au dhp), et taux de croissance en hauteur et en dhp pour les petits arbres (moins de 7,5 cm au dhp). Généralement, les résidus moyens des nouveaux modèles FVS^{Ontario} étaient plus petits que les résidus moyens des modèles LS-TWIGS originaux de FVS, ce qui signifie que les nouveaux modèles ont donné une représentation plus précise des effets de la variation régionale sur l’indice de site, la densité de peuplement et l’âge pour la plupart des espèces. De plus, l’analyse de cohérence biologique a révélé que toutes les variables dépendantes ont varié de façon logique en fonction des changements de l’indice de site, la densité de peuplement, la surface terrière ou l’âge.

INTRODUCTION

Many research projects have been conducted over the last four decades to develop stand growth models. All these projects aimed at investigating and providing decision support tools that would predict tree and stand growth better than the traditional stand tables currently in use. Among the various models developed in North America, the Forest Vegetation Simulator (FVS) continues to attract considerable attention from agencies seeking approaches to growth modeling due to its flexibility in modeling the response of silvicultural treatments for a range of species and forest conditions throughout the United States and most recently western Canada.

While there is a wide range of models and approaches available, relatively little effort has been devoted to the validation and calibration of any specific model, particularly in Canada. These two important steps are usually necessary, as they ensure that the predictions from the models are as precise as possible. This greater precision allows forest managers to better justify the investments required for silvicultural treatments. For these reasons, a previous exercise was conducted to validate the Lake States variant of FVS for the major forest types in Ontario (Lacerte *et al*. 2004). Results indicated that there were significant problems with the predictions of the Lake States-TWIGS (LS-TWIGS) variant of FVS for Ontario's forest conditions. In particular, predicted mortality rates were much greater than observed and errors between predicted and observed diameter at breast height (dbh) growth estimates were relatively large (Lacerte *et al.* 2004). Based on these results, a calibration exercise was undertaken to adapt FVS for Ontario's forest conditions.

The datasets used for the calibration of the LS-TWIGS variant of FVS included several species from central Ontario and the boreal forest of northern Ontario: black spruce (*Picea mariana* [Mill.] B.S.P.), jack pine (*Pinus banksiana* Lamb.), balsam fir (*Abies balsamea* [L.] Mill.), white spruce (*Picea glauca* [Moench] Voss), trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), sugar maple (*Acer saccharum* Marsh.), eastern white pine (*Pinus strobus* L.), red pine (*Pinus resinosa* Ait.), American beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britt.), basswood (*Tilia americana* L.), ironwood (*Ostrya virginiana* [Mill.] K. Koch), silver maple (*Acer saccharinum* L.), balsam poplar (*Populus balsamifera* L.), red oak (*Quercus rubra* L.), black cherry (*Prunus serotina* Ehrh.), bitternut hickory (*Carya cordiformis* [Wangenh.] K. Koch) and white ash (*Fraxinus americana* L.).

The objectives of the present study were to derive new models for dbh growth rate, survival rate, stem height (as a function of dbh) and species group density index (SGDI) and conduct biological consistency analyses to examine if the patterns of prediction of the new models were biologically consistent for different conditions of tree size, site index, age, stand density, average stand dbh or basal area.

MATERIALS AND METHODS

The derivation of new models for FVS$^{\text{Ontario}}$ was undertaken for several species: black spruce, jack pine, balsam fir, white spruce, trembling aspen, white birch, sugar maple, white pine, red pine, American beech, yellow birch, basswood, ironwood, silver maple, balsam poplar, red oak, black cherry, bitternut hickory and white ash. The entire databank originated from nine different sources that consisted mostly of long-term permanent sample plots (PSPs) containing 308,660 trees. Two groups of datasets were constructed for the present study: a Boreal dataset and a Great Lakes-St. Lawrence dataset. The Boreal dataset included PSP data from five sources that contained growth records for coniferous and hardwood stands in northern Ontario: AmCan (AC), Beckwith-Roebbelen (BR), Beckwith-Roebbelen Limestone (BRL) Lake, KimClark (KC), and Spruce Falls Power and Paper Co. (SFPP) (Table 1). The Great Lakes-St. Lawrence dataset consisted of PSP data for both conifer and hardwood species associations common to the Great Lakes-St. Lawrence forests on the Canadian Shield. Growth data from the following PSP data sources were used: ACHRAY (AH), ARGS (AR), Beckwith hardwood (BE) and Red pine plantations (PR) (Table 1). The majority of the records for both datasets were collected in pure and mixed natural stands. Plantation records were available in the BR, BRL and PR datasets for black spruce, jack pine, red pine and white spruce. Several datasets in the Great Lakes-St. Lawrence dataset were obtained from silvicultural experiments that were undertaken in the 1950s, 1960s and 1970s. For most species, there was a relatively large variation in age, stand density and site index (Table 1). For site index, the relatively wide variation reflected site productivity levels for poor, average and rich sites. The variability in stand density for different ages indicated that the databank covered different conditions of competition and self-thinning at different development stages. We assumed that no management activity to reduce density occurred.

Computation of dependent and independent variables

Some dependent and independent variables were computed using individual-tree and stand data before the derivation of models could be initiated. These variables included: dbh growth rate, survival rate and, for each tree within a stand, the basal area of all the trees that were greater than itself (BAL).

First, two sub-datasets were created: one for the large-tree models and one for the small-tree models. The large-tree model subset was created for all the trees equal to or greater than 7.5 cm in dbh, while those smaller than 7.5 cm in dbh were grouped into the small-tree model subset. Derivation of dbh growth rate and survival rate models for large and small trees of each species required remeasured individual-tree dbh data. Thus, all the trees identified with a minimum of two measurements within sample plots were extracted. In most cases, there were three measurement observations for each tree used in the sub-dataset. Using two successive measurements, the observed annual dbh growth rate of individual trees was computed as:

$$\Delta \mathrm{dbh} = \frac{\mathrm{dbh}_2 - \mathrm{dbh}_1}{\mathrm{T}_2 - \mathrm{T}_1}$$

where Δdbh is the annual dbh growth rate (cm year^{-1}), dbh_2 and dbh_1 the dbh at time T_2 and T_1, respectively.

Table 1. Summary of data used for the calibration of FVS^{Ontario}.

Leading species	Origin	Leading species proportions by basal area (%)	Age (year)	Stand density (stems ha^{-1})	qdbh[1] (cm)	SI[2] (m)	Basal area (m^2 ha^{-1})	Top height (m)	Total volume (m^3 ha^{-1})	Merch. volume (m^3 ha^{-1})	Origin of dataset	Number of sample plots
Black spruce	Natural	>70	98 (29,213)*	3826 (338,10378)	11.4 (4.2,20.9)	12 (6,19)	30.7 (3.6,48.6)	17.3 (7.7,27.7)	194 (22,357)	129 (0,305)	Boreal	58
Black spruce - Other conifers**	Natural	>50	97 (40,176)	3005 (675,7833)	13.9 (5.3,24.5)	14 (8,22)	36.7 (14.4,49.0)	19.9 (11.8,24.7)	266 (62,404)	195 (5,372)	Boreal	17
Black spruce - Other hardwoods[£]	Natural	>50	87 (61,111)	2008 (667,3855)	16.0 (12.6,18.8)	15 (13,20)	38.4 (16.5,48.2)	20.9 (18.7,23.8)	283 (127,372)	188 (90,275)	Boreal	8
Black spruce	Plantation	>70	27 (9,46)	2972 (744,10975)	8.7 (1.5,15.5)	13 (6,25)	16.8 (0.4,42.0)	9.2 (2.1,17.2)	73 (1,216)	27 (0,156)	Boreal	43
Black spruce - Other conifers	Plantation	>50	28 (19,36)	7600 (6100,9050)	6.7 (3.8,9.6)	14 (10,15)	27.2 (10.2,44.1)	8.8 (4.7,11.9)	119 (30,236)	31 (0,65)	Boreal	2
Jack pine	Natural	>70	74 (29,152)	2653 (633,6538)	13.7 (7.2,22.9)	16 (11,20)	32.9 (14.3,45.5)	19.2 (8.2,25.6)	263 (114,416)	201 (16,382)	Boreal	44
Jack pine - Other conifers	Natural	>50	99 (35,135)	2468 (588,4613)	14.7 (10.2,22.8)	14 (12,21)	38.3 (17.8,44.2)	20.4 (17.1,23.1)	300 (115,374)	226 (78,322)	Boreal	13
Jack pine - Other hardwoods	Natural	>50	63 (36,114)	2377 (976,3904)	14.1 (9.6,20.1)	17 (15,19)	32.5 (28.5,37.5)	19.6 (14.8,23.8)	255 (180,340)	161 (72,267)	Boreal	4
White spruce	Natural	>70	21 (6,47)	3857 (500,8600)	6.5 (0.9,18.3)	6 (2,19)	15.8 (0.0,47.9)	8.2 (1.7,17.1)	66 (1,277)	24 (0,191)	Boreal and Great Lakes-St. Lawrence	28
White spruce - Other conifers	Natural	>50	19 (6,33)	4909 (625,8100)	5.0 (1.2,9.1)	8 (3,13)	13.4 (0.1,35.1)	10.3 (1.9,18.8)	61 (1,191)	24 (0,89)	Boreal and Great Lakes-St. Lawrence	3
White spruce - Other hardwoods	Natural	>50	17 (11,33)	4953 (3600,6550)	5.0 (2.7,9.8)	9 (9,9)	10.7 (3.5,28.0)	9.9 (6.8,17.6)	52 (10,153)	14 (0,47)	Boreal and Great Lakes-St. Lawrence	3
Trembling aspen	Natural	>70	72 (30,214)	3127 (272,8735)	13.9 (4.7,26.9)	19 (6,24)	35.7 (5.0,50.3)	21.9 (12.6,29.3)	305 (63,500)	181 (0,431)	Boreal and Great Lakes-St. Lawrence	39
Trembling aspen - Other conifers	Natural	>50	86 (28,193)	2500 (550,6822)	14.7 (5.8,25.0)	18 (14,22)	37.2 (4.1,50.4)	22.3 (13.8,27.6)	317 (109,502)	212 (0,467)	Boreal and Great Lakes-St. Lawrence	18

Leading species	Origin	Leading species proportions by basal area (%)	Age (year)	Stand density (stems ha^{-1})	qdbh[1] (cm)	SI[2] (m)	Basal area (m^2 ha^{-1})	Top height (m)	Total volume (m^3 ha^{-1})	Merch. volume (m^3 ha^{-1})	Origin of dataset	Number of sample plots
Trembling aspen - Other hardwoods	Natural	>50	46 (23,98)	4637 (700,7228)	10.4 (6.7,21.7)	20 (8,22)	31.6 (9.0,47.5)	18.5 (10.8,25.9)	215 (95,454)	63 (0,394)	Boreal and Great Lakes-St. Lawrence	7
White birch	Natural	>70	-	992 (992, 992)	8.6 (8.6, 8.6)	-	5.8 (5.8, 5.8)	-	-	-	Boreal and Great Lakes-St. Lawrence	1
White birch - Other hardwoods	Natural	>50	94 (81,114)	1524 (658,3632)	12.5 (8.8,19.0)	19 (18,19)	20.1 (6.6,38.8)	25.2 (23.7,28.1)	317 (312,325)	233 (211,254)	Boreal and Great Lakes-St. Lawrence	5
Sugar maple	Natural	>70	79 (27,120)	782 (42,3989)	22.8 (8.3,50.5)	20 (17,24)	21.7 (2.2,44.5)	22.5 (13.3,28.1)	236 (106,416)	103 (0,216)	Great Lakes-St. Lawrence	196
Sugar maple - Other conifers	Natural	>50	-	659 (542,825)	17.9 (11.7,25.4)	-	19.2 (5.8,30.5)	-	-	-	Great Lakes-St. Lawrence	2
Sugar maple - Other hardwoods	Natural	>50	64 (32,120)	3117 (125,9075)	16.4 (5.9,36.9)	19 (15,20)	26.5 (6.6,36.6)	19.0 (14.5,24.2)	178 (97,274)	50 (0,182)	Great Lakes-St. Lawrence	36
White pine	Natural	>70	102 (78,125)	940 (175,1950)	20.4 (11.8,43.5)	14 (10,17)	27.4 (7.5,42.6)	25.3 (16.4,32.7)	307 (123,486)	246 (44,449)	Great Lakes-St. Lawrence	42
White pine - Other conifers	Natural	>50	122 (115,125)	1216 (372,2950)	16.3 (10.1,31.8)	12 (12,13)	23.9 (6.4,46.3)	27.2 (26.2,28.6)	395 (327,416)	341 (293,372)	Great Lakes-St. Lawrence	14
White pine - Other hardwoods	Natural	>50	-	1402 (625,1850)	17.1 (15.1,23.9)	-	32.5 (20.7,47.0)	-	-	-	Great Lakes-St. Lawrence	4
White pine	Plantation	>70	-	1615 (346,2593)	18.0 (14.1,32.1)	-	36.9 (19.7,48.9)	-	-	-	Great Lakes-St. Lawrence	9
Red pine	Natural	>70	-	1354 (450,2825)	18.0 (3.9,30.7)	-	32.4 (0.9,49.6)	-	-	-	Great Lakes-St. Lawrence	45
Red pine - Other conifers	Natural	>50	-	1254 (608,1842)	15.0 (8.8,22.3)	-	21.7 (8.4,33.9)	-	-	-	Great Lakes-St. Lawrence	6
Red pine	Plantation	>70	47 (23,74)	977 (318,2800)	24.1 (13.4,38.5)	22 (18,25)	39.1 (25.3,57.4)	19.7 (11.1,26.2)	338 (168,542)	310 (143,501)	Great Lakes-St. Lawrence	16

Leading species	Origin	Leading species proportions by basal area (%)	Age (year)	Stand density (stems ha^{-1})	qdbh[1] (cm)	SI[2] (m)	Basal area (m^2 ha^{-1})	Top height (m)	Total volume (m^3 ha^{-1})	Merch. volume (m^3 ha^{-1})	Origin of dataset	Number of sample plots
American beech	Natural	>70	-	1575 (1425,1700)	14.8 (14.3,15.4)	-	26.9 (26.5,27.2)	-	-	-	Great Lakes-St. Lawrence	1
Yellow birch	Natural	>70	-	670 (583,900)	16.4 (14.6,21.6)	-	15.3 (10.8,33.1)	-	-	-	Great Lakes-St. Lawrence	2
Yellow birch - hardwoods	Natural	>50		497 (142,583)	18.5 (17.8,21.5)	-	12.6 (5.1,14.5)				Great Lakes-St. Lawrence	2
Red oak	Natural	>70	75 (73,78)	236 (151,289)	28.5 (27.0,30.1)	22 (22,22)	14.7 (10.6,18.0)	26.5 (26.1,26.6)	141 (108,164)	91 (74,107)	Great Lakes-St. Lawrence	2
Red oak - Hardwoods	Natural	>50	46 (39,54)	3227 (733,4350)	12.5 (10.8,14.3)	18 (18,18)	36.8 (9.1,47.3)	17.1 (16.0,18.4)	264 (223,312)	33 (5,78)	Great Lakes-St. Lawrence	2
Black cherry	Natural	>70	-	600 (600, 600)	24.3 (24.3, 24.3)	-	27.9 (27.9, 27.9)	-	-	-	Great Lakes-St. Lawrence	1
Black cherry - Other hardwoods	Natural	>50	-	657 (650, 850)	23.7 (20.4, 23.9)	-	29.0 (27.9, 29.1)	-	-	-	Great Lakes-St. Lawrence	2
Tolerant hardwoods - Other hardwoods§	Natural	>50	-	638 (625,650)	23.3 (21.9,24.8)	-	27.3 (24.5,30.3)	-	-	-	Great Lakes-St. Lawrence	2
Mix - Conifers¤	Natural	>50	95 (78,114)	1714 (658,2681)	13.9 (9.1,20.0)	15 (14,19)	27.7 (5.2,40.8)	21.8 (19.8,24.4)	299 (251,336)	208 (160,272)	Boreal and Great Lakes-St. Lawrence	8
Mix - Hardwoods¥	Natural	>50	99 (89,112)	1287 (450,2375)	16.6 (12.4,20.8)	14 (14,15)	25.0 (12.6,32.9)	21.5 (19.9,23.2)	240 (236,244)	154 (144,169)	Boreal and Great Lakes-St. Lawrence	7

Legend:

[1]qdbh: Quadratic mean diameter

[2]SI: Site index

*Values within brackets are the minimum and maximum values obtained.

**More than 30% of basal area included other conifers.

£More than 30% of basal area included hardwood species.

§More than 50% of basal area included sugar maple, American beech and silver maple and more than 30% of basal area included trembling aspen, white birch, yellow birch, basswood, ironwood, silver maple, balsam poplar, red oak, black cherry, bitternut hickory and white ash.

¤More than 50% of basal area included black spruce, jack pine, balsam fir, white spruce, white pine, red pine and tamarack.

¥More than 50% of basal area included trembling aspen, white birch, sugar maple, American beech, yellow birch, basswood, ironwood, silver maple, balsam poplar, red oak, black cherry, bitternut hickory and white ash.

Individual-tree survival rate was computed using the equation proposed by Buchman (1983), Buchman (1985) and Buchman *et al*. (1983) for the estimation of individual-tree survival rate:

$$SR = \left[\sum_i X_i / \sum_i N_i\right]^{\left[\sum_i N_i / \sum_i i \bullet N_i\right]}$$

where SR is the survival rate (between 0 and 1), N_i and X_i are the number of trees alive at the beginning and at the end of the status observation interval, respectively, and *i* is the interval length (year).

For each tree, the basal area for all the trees greater than itself was computed (BAL [m^2 ha^{-1}]), as this variable was used as an independent variable in the models for survival rate, small-tree dbh growth rate and height growth rate. BAL has been shown to be a significant independent variable in other studies that dealt with the computation of survival rate (e.g., Monserud and Sterba 1999; Eid and Tuhus 2001).

Model derivation

The different basic model forms used to predict several dependent variables as a function of tree and stand variables were similar to those originally developed in previous versions of FVS (Table 2). All the model forms listed in Table 2 were analyzed using the *model* procedure of SAS (SAS Institute Inc. 2001) (See example in Appendix 1). As there were repeated measurements, the Durbin-Watson and Godfrey tests were computed. If autocorrelation was significant, a model with second-order autoregressive error was used. For particular cases, when the estimate of a parameter associated with an independent variable was not statistically significant ($\alpha > 0.05$), the following steps were undertaken. First, the form of the model associated with the independent variable was modified and then the program was run again. Thus, an iterative process was performed. If the different trials did not result in a more significant model, then the independent variable associated with the non-significant parameter was removed.

Table 2. Basic model forms used to develop models predicting dbh growth rate, survival rate, stem height and SGDI (species group density index) for FVS[Ontario] as a function of different tree and stand variables.

Dependent variables	Models
Dbh growth rate (cm year^{-1})	$\Delta\text{dbh} = \exp\left(\alpha_1 \text{dbh}^{\alpha_2} + \alpha_3 \text{si}^{\alpha 4} / \exp\left(\alpha_5 (\text{dbh} / \text{mean\_dbh})^{\alpha_6} + \alpha_7 \text{ba}^{\alpha_8}\right)\right) - 1 + \varepsilon$
Survival rate (proportion)	SR= $\left(1 + \left(1/\left(\exp\left(\alpha_1 dbh^2 + (\alpha_2 / bal) + \alpha_3 \Delta dbh^2\right)\right)\right)\right)^{-1} + \varepsilon$
Height-dbh models (m)	Ht= $\left(1 - \exp(-\alpha_1 \text{dbh})\right) \text{ba}^{\alpha_2} + \varepsilon$
SGDI (trees ha^{-1})	SGDI= $\alpha_1 (\text{mean\_dbh prop})^2 + \alpha_2 \text{ba} + \alpha_3 \text{prop}^2 + \varepsilon$
Small-tree height growth model (m year^{-1})	$\Delta\text{Ht} = \left(\exp\left(\alpha_1 \ln(\text{ht})^2 + \alpha_2 \text{ht bal} + \alpha_3 \ln(\text{bal})^2\right)\right) - 1 + \varepsilon$
Small-tree dbh growth model (cm year^{-1})	$\Delta\text{dbh} = \alpha_1 \ln(\text{dbh}) + \alpha_2 \text{bal}^2 + \varepsilon$

Legend

Δdbh	Annual dbh increment rate (cm yr^{-1})
dbh	Diameter at breast height (cm)
si	Site index (m)
mean_dbh	Average stand dbh (cm)
ba	Basal area (m^2 ha^{-1})
bal	Basal area of the trees greater than the subject tree (m^2 ha^{-1})
ht	Stem height-1.3 (m)
ΔHt	Height growth rate (m yr^{-1})
prop	Species percentage based on number of trees per ha (%)
α_n	Parameters
ε	It is assumed that ε is ~ N $(0,\sigma^2_\varepsilon)$

Biological consistency analysis

When the model derivation process resulted in statistically significant models for all species and variables, a biological consistency analysis was performed to evaluate if the patterns of prediction were logical for a large amplitude of dbh under different conditions of site index, age, stand density, average stand dbh or basal area. Extreme values were used to test the model's consistency under a wide range of conditions. For instance, it was important to ensure that dbh growth rate increased with increase in dbh, but decreased with an increase in basal area. When the effect of an independent variable resulted in an inconsistent biological pattern for a particular species and dependent variable, the form of the model was changed and tested again until a consistent biological pattern was obtained.

RESULTS AND DISCUSSION

Description of the new models

Dbh growth rate

All the models developed for dbh growth rate for the suite of species were highly significant (Appendix 2). For about half of the models, dbh, average stand dbh and basal area were variables that contributed to a statistically significant increase in the quality of the fit of the models. Some species had models with only dbh and average stand dbh or dbh and basal area as independent variables. This was the case for balsam fir, white birch, planted white pine, yellow birch and bitternut hickory. The parameter estimate for site index was significant only for black spruce in natural stands, jack pine and balsam poplar.

Site index was excluded for planted black spruce, balsam fir, planted white spruce, trembling aspen and white birch because no model form resulted in significant parameters for this independent variable. Even though site index was quite variable for these species, the range of data for some site index values was insufficient to be effective in the derivation of the models. For planted white and red pines, site index was not included due to its low variability for both species. As more PSP data becomes available from a wider range of site qualities, these relationships will be tested again and altered if necessary.

Survival rate

For survival rate, nearly all the models contained dbh, dbh growth rate and BAL as independent variables with significant parameters (Appendix 2). Only white birch differed in this respect, as only dbh and dbh growth rate were significant. All the models derived were highly significant ($\alpha<0.05$).

Height-dbh

The majority of the height-dbh models had the same independent variables associated with significant parameters: dbh and basal area (Appendix 2). For black spruce, white birch, yellow birch and red oak, there was no significant independent variable that represented the effect of stand density, such as basal area. For black spruce, jack pine, trembling aspen and white birch, the parameters associated with site index were significant. For sugar maple, the parameter for quadratic mean diameter was significant.

Species group density index

The SGDI model differed substantially among the species, but all the models contained basal area and the species proportion as statistically significant independent variables (Appendix 2).

Small-tree dbh and height growth rates

The height growth rate models for small trees were derived for only four species, based on those that had sufficient data (Appendix 2). The models differed among the species, but all contained at least height and BAL as independent variables. The dbh growth rate model for small trees was also derived for the same four species (Appendix 2). All the models contained dbh and BAL as independent variables.

All the models derived for the suite of species-specific models were highly significant and better represented the conditions in Ontario's forests for most species. This is supported by the comparison of the mean residuals of the new calibrated models with the mean residuals that were computed using the original FVS models (Table 3). As indicated in Table 3, the mean residuals of the new calibrated models were lower than the mean residuals of the original FVS models, except for the height-dbh model for black spruce in natural stands and sugar maple.

Table 3. Comparison of the mean residuals of the new calibrated models with the mean residuals computed using the original FVS models.

dbh growth rate model

		Mean residuals (cm year^{-1})	
Species	**Origin**	**New calibrated models**	**Original FVS models**
Black spruce	Natural	-0.0823	-0.1292
Black spruce	Plantation	-0.1636	-0.2219
Jack pine	Natural	-0.0007	0.0021
Balsam fir	Natural	0.0085	-0.1774
White spruce	Plantation	-0.0620	-0.0686
Trembling aspen	Natural	-0.0779	-0.0942
White birch	Natural	0.0043	-0.0669
Sugar maple	Natural	-0.0384	-36.6786
White pine	Natural	-0.0361	0.0434
White pine	Plantation	-0.0031	-0.0354
Red pine	Plantation	-0.0038	-0.0272
American beech	Natural	-0.0568	-46.7013
Yellow birch	Natural	-0.0354	-32.6014
Basswood	Natural	-0.1674	-0.1705
Silver maple	Natural	-0.0173	-0.1096
Balsam poplar	Natural	-0.0579	-0.2567
Red oak	Natural	0.0302	-0.1148
Black cherry	Natural	-0.0281	-0.8733
Bitternut hickory	Natural	0.0212	-0.066

Survival model

		Mean residuals (Proportion)	
Species	**Origin**	**New calibrated models**	**Original FVS models**
Black spruce	Natural	0.0000*	-0.0304
Jack pine	Natural	0.0000*	-0.0659
Balsam fir	Natural	0.0000*	-0.0148
White spruce	Plantation	-0.0081	-0.0544
Trembling aspen	Natural	0.0000*	-0.0552
White birch	Natural	0.0000*	-0.0078
Sugar maple	Natural	0.0000*	-0.0194
White pine	Natural	0.0001	-0.0122
Red pine	Natural	0.0000*	-0.0008
Red pine	Plantation	-0.0015	-0.0021
American beech	Natural	0.0000*	-0.0108
Balsam poplar	Natural	0.0000*	-0.0692

Height-dbh models

		Mean residuals (m)	
Species		**New calibrated models**	**Original FVS models**
Black spruce	Natural	2.7162	1.7527
Jack pine	Natural	0.7497	-3.9704
Balsam fir	Natural	-1.3895	-6.2414
White spruce	Plantation	-1.4584	-1.5549
Trembling aspen	Natural	2.0681	-2.8942
White birch	Natural	-0.4571	0.5579
Sugar maple	Natural	-2.8431	-2.6737
White pine	Natural	-1.8194	-5.0667
Red pine	Natural	0.1356	-5.5991
Red pine	Plantation	0.0303	-3.2268
American beech	Natural	-1.4553	-5.9650
Yellow birch	Natural	-0.6152	-1.5820
Basswood	Natural	0.0669	-5.5175
Iron/Ash/Silver maple	Natural	0.1052	-2.5920
Red oak	Natural	-0.7535	-2.7963

SGDI

	Mean residuals (trees ha^{-1})	
Stocking group	**New calibrated models**	**Original FVS models**
Black spruce	-148.3109	-275.6308
Jack pine	804.0518	-1153.7700
White spruce	-20.5113	-521.8449
Aspen	720.6408	-1275.4000
White birch	-15.7748	-45.6391
Red and White pine	175.1165	-2108.8000
Northern hardwoods	-54.5861	-1278.6200
Red oak	-32.7051	107.9950

Small-tree height growth

	Mean residuals (m $year^{-1}$)	
Species	**New calibrated models**	**Original FVS models**
Black spruce	-0.0130	-0.0151
Balsam fir	0.0143	-0.0637
White spruce	0.0287	0.0935
White pine	-0.0115	-0.3601

Small-tree dbh growth

	Mean residuals (cm $year^{-1}$)	
Species	**New calibrated models**	**Original FVS models**
Black spruce	-0.0256	3.9295
Balsam fir	-0.0358	0.4078
White spruce	0.0571	1.3997
White pine	-0.0244	0.2916

* The value under 0.001 in absolute value was reported as zero.

Biological consistency analysis

Dbh growth rate models

The dbh growth rate model for black spruce in natural stands demonstrated a consistent pattern (Appendix 3.1, Figures a, b & c). For low site indexes, dbh growth rate always decreased with an increase in basal area, increased with an increase in dbh until a threshold value and remained relatively constant thereafter. A pattern of increasing dbh growth rate with an increase in average stand dbh was observed. For high site index values, dbh growth rate increased with dbh until a threshold value, and then decreased thereafter. The pattern of change with respect to basal area and average stand dbh was similar to that for low site index values. The decrease in dbh growth rate with increase in dbh in some instances appears inconsistent and may be explained by the fact that this pattern occurred in conditions of site index and basal area that were beyond the range of the values of the calibration dataset. The biological pattern of the new models was much more consistent than the pattern of the original FVS model (Appendix 3.1, Figure d). For the original FVS model, the pattern of increase in dbh with a decrease in basal area was consistent only until a dbh of about 40 cm was reached. Then, dbh growth rate increased with an increase in basal area.

For planted black spruce, dbh growth rate increased with increasing dbh, but decreased with increasing basal area and average stand dbh (Appendix 3.2, Figures a, b & c). The original FVS model had the same consistent pattern, but the growth rates predicted were much lower than the new model and the increase in dbh growth rate with increase in dbh levelled off at a relatively low dbh (Appendix 3.2, Figure d).

For jack pine, dbh growth rate always increased with an increase in dbh and site index, but decreased with increasing average stand dbh (Appendix 3.3, Figures a, b & c). Compared with the new model, the original FVS model was much less consistent (Appendix 3.3, Figure d). The relationship of dbh growth rate to dbh indicated a slight decrease in small dbh values, an increase up to a peak value of about 20 cm, followed by a sharp decrease.

Dbh growth rate for balsam fir was characterized by a consistent pattern with increasing dbh and basal area, except for small dbhs for the two largest basal area values (Appendix 3.4, Figure a). The original FVS model indicated an increase in dbh growth rate up to a peak value of about 20 cm for the two largest basal area values, followed by a decrease (Appendix 3.4, Figure b). Planted white spruce had a consistent pattern (Appendix 3.5, Figures a, b & c). While dbh growth rate increased sharply with dbh in the lowest average stand dbh values, it changed very little with increasing dbh in the two greatest average stand dbh values. The pattern obtained with the new calibrated model differed entirely from the pattern obtained with the original FVS model (Appendix 3.5, Figure d). However, the increasing pattern up to a peak dbh followed by a decrease with the original FVS model is similar to the pattern observed for other species.

Dbh growth rate for trembling aspen generally increased with increasing dbh, but decreased with an increase in basal area and average stand dbh (Appendix 3.6, Figures a, b & c). The pattern observed using the original FVS models was not consistent: rapid early increase with increasing dbh, followed by a more or less regular increase or decrease (Appendix 3.6, Figure d). For white birch, the small amount of data available did not allow us to conduct a full-scale analysis of biological consistency (Appendix 3.7, Figure a). Nevertheless, the pattern obtained was much more consistent than the pattern obtained using the original FVS model (Appendix 3.7, Figure d). For small dbh values, dbh growth rate decreased with increase in average stand dbh. However, the trend was reversed for the lowest average stand dbh beyond an average stand dbh of 15 cm.

The patterns obtained for the new calibrated model for sugar maple were generally consistent (Appendices 3.8, Figures a, b & c). There was a general pattern of decrease in dbh growth rate with increase in average stand dbh and basal area. For average stand dbh of 5 cm, the pattern was consistent and dbh growth rate increased with increase in dbh. However, for the two largest average stand dbh values, there was a pattern of decrease in dbh growth rate with dbh. This pattern can be explained by the relatively old ages of the trees and the lack of data for trees in the high average stand dbh and basal area values. Compared with the new models, the patterns obtained from the original FVS models were completely different (Appendix 3.8, Figure d).

Several species were characterized by the same general pattern with the new calibrated models: white pine in natural stands, American beech, basswood, silver maple and red oak (Appendices 3.9, 3.12, 3.14, 3.15 & 3.17, Figures a, b & c). Dbh growth rate always decreased with increasing basal area. For relatively low average stand dbh, dbh growth rate increased with an increase in dbh. As average stand dbh increased, there was either no pattern of change in dbh growth rate with dbh or a very small decrease. For each of these species, the patterns obtained with the original FVS models differed substantially from those obtained with the new models (Appendices 3.9, 3.12, 3.14, 3.15 & 3.17, Figure d).

Relatively few data were available for planted white pine (Appendix 3.10, Figure a). For the different conditions of average stand dbh illustrated, dbh growth rate increased with an increase in dbh and decreased with average stand dbh. The pattern obtained with the original FVS models was inconsistent, as predicted dbh growth rate decreased with decrease in average stand dbh for a large amplitude of dbh (Appendix 3.10, Figure b). For planted red pine, dbh growth rate generally decreased with increasing basal area, average stand dbh and dbh (Appendix 3.11, Figures a, b & c). However, for the lowest average stand dbh and basal area values, dbh growth rate increased with increase in dbh (Appendix 3.11, Figure a). The decrease in dbh growth rate with increase in dbh was inconsistent. This pattern can be explained by the paucity of data in the calibration dataset with respect to high basal area and average stand dbh values. Compared with the new calibrated models, the original FVS models generally predicted lower dbh growth rates as basal area was increased (Appendix 3.11, Figure d). For yellow birch, the pattern of dbh growth rate with increasing dbh shifted from an increasing trend for low basal area values to a decreasing one as basal area increased (Appendix 3.13, Figure a). The decrease in dbh growth rate with increase in dbh was inconsistent and may be explained by the fact that these predictions were made outside the range of the calibration dataset. The pattern obtained with the new calibrated model was more biologically consistent than the pattern obtained with the original FVS model, which predicted fluctuations for a certain range of dbh values (Appendix 3.13, Figure b).

Balsam poplar was characterized by a different pattern in comparison with most of the other species (Appendix 3.16, Figures a, b & c). Dbh growth rate increased with an increase in dbh until a threshold value, and decreased thereafter. Relative to the new calibrated models, the patterns obtained using the original FVS models were biologically inconsistent, as there were large fluctuations in predicted dbh growth rate with increase in dbh (Appendix 3.16, Figure d). For black cherry, dbh growth rate decreased with an increase in average stand dbh and basal area and increased with an increase in dbh (Appendix 3.18, Figures a, b & c). However, there was a substantial difference between dbh growth rate predicted in the lowest basal area value and the two largest basal area values. The new model predicted much lower dbh growth rate than the original FVS model (Appendix 3.18, Figure d). Also, the original FVS model was characterized by an inconsistent pattern for the lowest average stand dbh. Dbh growth rate for hickory always increased with increasing dbh and decreased with an increase in average stand dbh (Appendix 3.19, Figure a). Predicted dbh growth rate using the original FVS model was greater than the new model, except for the lowest average stand dbh (Appendix 3.19).

Survival models

The models for survival rate were consistent for all the species (Appendix 4). Predicted survival rates were generally greater than 0.90. Even though predicted survival rates were very close for all conditions, all the species were characterized by a pattern of increase in survival rate with increase in dbh and dbh growth rate and a pattern of decrease with increase in BAL (Appendix 4). Predictions of survival rate obtained with the new calibrated models were much greater than those obtained using the original FVS models. This was particularly evident for black spruce in natural stands, jack pine, balsam fir, planted white spruce, sugar maple, white pine in natural stands, planted red pine and balsam poplar.

Height-dbh models

The models predicting height as a function of diameter were consistent for all the species (Appendix 5). Tree height increased with increasing dbh, basal area and site index. Compared with the original FVS models, the same pattern of variation with respect to increase in dbh was obtained with the new calibrated models. However, the amplitude of variation in height predicted by the new models for different conditions of basal area were larger for most species than the amplitude obtained in the original FVS models (Appendix 5).

Species group density index models

For SGDI, the black spruce, jack pine, trembling aspen, white birch, red and white pines, northern hardwoods and red oak species groups were characterized by a pattern of increase in relative density indexes with an increase in the proportion of the species of interest and basal area (Appendix 6). Also, SGDI generally decreased with increasing quadratic mean diameter and average stand dbh. The white spruce species group generally had a pattern of increase in SGDI with an increasing proportion of the species of interest (Appendix 6.3). However, for some basal area values, the increase in SGDI was followed by a decline after a peak value was reached. While there was a pattern of increase in SGDI with increase in basal area for all species, there was one exception. For white spruce, SGDI decreased with increase in basal area when the maximum average stand dbh was 30 and 28 cm, respectively. This pattern was not biologically consistent, and may be due to the fact that too little data for some conditions of basal area and average stand dbh were available for the derivation of the model for this species. The models developed for this species will have to undergo further calibration with the addition of new data sources.

Small-tree height growth models

The height growth rate models for small trees were generally biologically consistent (Appendix 7). For black spruce and balsam fir, and white spruce and white pine when BAL was lower than 20 m^2 ha^{-1}, height growth rate increased with increase in height and decrease in BAL (Appendices 7.1 & 7.2). However, for these species, there was a large shift from the predictions for the smallest BAL class to the next BAL class relative to the gradual change or small differences for the predictions for subsequent BAL levels. The large shift noticed above detracts from the gradual effect of change in independent variables observed for other models in the present study. The effect of change in BAL was more regular for white spruce (Appendix 7.3). However, the decrease in height growth rate past a threshold height was not biologically consistent. This suggests that the small-tree height limit for white spruce is probably too high. Therefore, the large-tree model should probably be applied for a limit of 2.5 m in height. For white pine, the pattern obtained was biologically consistent for only two BAL values (Appendix 7.4). The trend illustrated by Appendix 7.4 suggests that the model should be applied up to a limit of BAL of 25 m^2 per ha.

Small-tree dbh growth models

The small-tree dbh growth models appeared biologically consistent for all the species, except for white pine (Appendix 8). Dbh growth rate increased with increase in dbh, but decreased with increase in BAL. The fact that predictions for white pine resulted in a decrease in dbh growth rate with an increase in dbh probably resulted from the fact that too little data were available for the derivation of the model. Again, this species will have to be revisited when more data become available.

Suggestions for future directions in the calibration of $FVS^{Ontario}$

Even though the new models derived in the study performed generally better than the original FVS models, there is still a need to continue and expand the calibration exercise. As previously mentioned, the dataset used for some species did not represent sufficiently well the variation in stand characteristics to enable us to derive a model that is expected to cover all the possible ranges of variation in site index, stand density and age usually found in Ontario’s forests. Suggestions for future directions cover four aspects:

Lack of data for calibration

The following table lists the species and the model type for which more data would be desirable.

Species	dbh growth rate	Survival rate	Height-dbh models	Small-tree dbh growth and height growth
Black spruce natural				
Black spruce plantations		*		
Jack pine natural				
Jack pine plantations				
Balsam fir				
White spruce natural				
White spruce plantations				
Trembling aspen				
White birch				
Sugar maple				
White pine natural				
White pine plantations				
Red pine natural				
Red pine plantations				
American beech				
Yellow birch				
Basswood				
Ironwood				
Silver maple				
Balsam poplar				
Red oak				
Black cherry				
Bitternut hickory				
Cedar				
Tamarack				
Black ash				
White ash				
Elm				
Striped maple				

*The grey boxes indicate that data was missing for this specific species.

Calibration of species groups

In situations where insufficient data exist to enable us to develop the suite of desired models, it becomes necessary to create similar species groups. Three groups were formed:

i. Other softwoods
ii. Commercial hardwoods
iii. Non-commercial hardwoods

Additional desirable data for species already calibrated

Although models were developed for many species, the following list of species and ranges of site index, age or stand density are still lacking complete coverage. It would be desirable to collect additional data so that more robust models would be derived for the following situations:

Boreal dataset:

a) Black spruce natural:
    i. Site index lower than 10 m and age lower than 50 years.
    ii. Site index greater than 20 m and age greater than 40 years.
b) Black spruce plantations:
    i. Site index greater than 20 m for different ages.
    ii. Age greater than 40 years for different site indexes.
c) Jack pine natural:
    i. Site index lower than 10 m or greater than 20 m for different ages.
d) Trembling aspen:
    i. Site index lower than 10 m and age lower than 80 years.
    ii. Site index greater than 20 m and age greater than 50 years.
e) White spruce plantations:
    i. Site index greater than 15 m for different ages.
    ii. Age greater than 40 years for different site indexes.

Great Lakes-St. Lawrence dataset:

a) Black cherry:
    i. All conditions
b) Red oak:
    i. All conditions
c) Red pine plantations:
    i. Site index lower than 20 m for different ages.
    ii. Age greater than 60 years for different site indexes.
d) Sugar maple:
    i. Site index lower than 15 m.
    ii. Site index lower than 20 m and age lower than 50 years.
    iii. Site index greater than 20 m and age greater than 70 years.
e) White pine natural:
    i. Site index lower than 10 m for different ages.
    ii. Site index greater than 10 m and age lower than 50 years.
    iii. Site index greater than 15 m for different ages.
f) Yellow birch:
    i. Site index lower than 15 m for different ages.
    ii. Site index greater than 15 m and age lower than 100 years.

Recommendations for the modelling of silvicultural response

Future efforts in data collection and modeling should focus on tree and stand response to silvicultural treatments. This will require data for different conditions of stand density and effects of thinning treatments of different levels from stands that were remeasured at least twice. While it is most desirable to use data from remeasured situations, short-term approaches to fill this need could be accomplished through stem analysis or increment core sampling.

CONCLUSION

This calibration work has created a version of FVS^{Ontario} to be operationally tested with known shortcomings. Improvements to the model parameters and model forms will continue as Ontario expands its plot network and remeasurement efforts. This version of the model is still incorporating Lake States-TWIGS model forms and parameters for a host of species that Ontario does not currently cover in its datasets. This data shortfall impacts the full suite of FVS models (e.g. large-tree model, small-tree model) and will be addressed over time. Efforts in the near future to develop broad species groups, such as "intolerant upland conifers" (based on tolerance and site), may provide a short-term stop-gap method to minimize our reliance on the Lake States-TWIGS models for the species for which we lack sufficient data.

Even though the research work involved in the development of this model was a great success, this work must continue to ensure that the predictive capacity of models improves significantly, particularly for changing environmental conditions, such as the effect of climate change. FVS^{Ontario} should and could provide the "growth engine" to other models looking to "grow" trees and stands into the future with a host of different potential influences (e.g. global warming, insect and disease outbreaks, fire).

ACKNOWLEDGEMENTS

Sincere thanks are extended to the Ontario Living Legacy Trust, the Ontario Ministry of Natural Resources, Tembec Forest Research Partnership, Inc. and the Canadian Ecological Centre for financial support for this project. The study was also supported by the Ecosystem Process Research Network of the Canadian Forest Service. We thank Susan Stevens Hummel, with the USDA Forest Service at the Pacific Northwest Station, Portland, Oregon, and Ronald E. McRoberts, with the USDA Forest Service at the North Central Research Station, St. Paul, Minnesota, for their comments on an earlier version of the manuscript. The editorial review of the manuscript by Pamela Cheers and Benoit Arsenault, editors at the Laurentian Forestry Centre, was greatly appreciated.

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Appendix 1. Example of a SAS program used to derive the different models.

```
/*proc model
dw=test durbin-watson*/
  proc model data=blackSpruce_b;
  TITLE1 "BLACK SPRUCE_N";
     parms A2=-1.5719  A3=-0.0857 A44=0.1708 D2=0.261 C3=0.0202;
            tauxcrois_dhp=(EXP(((a2*(CurrDiam)**a3)+(SI**a44))/
                  exp(((d2*CurrDiam/dhp_moy))+
                  (c3*(ba)) )))-1;
     fit tauxcrois_dhp START=(A2=-1.5719  A3=-0.0857 A44=0.1708 D2=0.261
C3=0.0202)/CORRS DW DWPROB OUT=PRED_TAUXCROIS_DBH OUTPREDICT
GODFREY
     METHOD=GAUSS CONVERGE=0.000001 MAXITER=10000 WHITE PRL=WALD
OUTEST=AUTO.TAUXDBH_BSPRUCEN;
            %ar(tauxcrois_dhp,2);
   run;
quit;
```

Appendix 2. Summary of new models calibrated for $FVS^{Ontario}$.

Large-tree models

<u>dbh growth rate*</u>

Species	Origin	Model	$\sqrt{MSE}$
Black spruce	Natural	$(\exp(-1.3894dbh^{-0.0538}+si^{0.1535}/\exp(0.1273(dbh/mean\_dbh)+0.0219ba)))-1$	0.0788
Black spruce	Plantation	$(\exp(0.6533dbh^{-0.7031}/\exp{-1.0769}(dbh/mean\_dbh)+0.00431ba^{1.6318}))-1$	0.0856
Jack pine	Natural	$(\exp((2.2952mean\_dbh^{-1.4313}+0.000064si^{2})/(\exp{-0.039}dbh)))-1$	0.0862
Balsam fir	Natural	$(\exp(0.0578ba+0.2131dbh/\exp(dbh\ ba)^{0.1886}))-1$	0.1256
White spruce	Plantation	$(\exp((dbh^{0.2628})/(\exp((-0.1522(\ dbh/mean\_dbh))+((ba\ dbh)^{0.1490})))\ ))-1$	0.1366
Trembling aspen	Natural	$(\exp((dbh\ ba)^{-0.3447}/\exp{-0.3333}(dbh/mean\_dbh)))-1$	0.1127
White birch	Natural	$(\exp(dbh^{-1.2617}+0.000072mean\_dbh\ dbh/\exp{-0.6411}(dbh/mean\_dbh)))-1$	0.1125
Sugar maple	Natural	$(\exp((dbh\ ba)^{-0.1885}/\exp{-0.0657}(dbh/mean\_dbh)+0.0137ba))-1$	0.2143
White pine	Natural	$(\exp((dbh\ ba)^{-0.2537}/\exp{-0.2010}(dbh/mean\_dbh)+0.0072ba))-1$	0.1304
White pine	Plantation	$(\exp(0.00356mean\_dbh/\exp{-1.1527}(dbh/mean\_dbh)))-1$	0.3755
Red pine	Plantation	$(\exp(-0.00863dbh+1.9255ba^{-0.4378}/\exp{-0.1322}(dbh/mean\_dbh)))-1$	0.1664
American beech	Natural	$(\exp(dbh^{-0.2821}/\exp{-0.1282}(dbh/mean\_dbh)+0.0284ba))-1$	0.2094
Yellow birch	Natural	$(\exp(-0.00003dbh^{2}+0.1136mean\_dbh^{0.1915}/\exp{-0.3248}(dbh/mean\_dbh)))-1$	0.2018
Basswood	Natural	$(\exp((dbh\ ba)^{-0.0234}/\exp{-0.1686}(dbh/mean\_dbh)+0.0555ba))-1$	0.1758
Silver maple	Natural	$(\exp(ba\ dbh^{-0.2875}/\exp{-0.4235}(dbh/mean\_dbh)))-1$	0.1522
Balsam poplar	Natural	$(\exp(-4.3221dbh^{-0.4410}+si^{0.2004}/\exp(dbh/mean\_dbh)))-1$	0.1202
Red oak	Natural	$(\exp(dbh^{-0.5068}/\exp{-0.2577}(dbh/mean\_dbh)+0.000297ba^{2}))-1$	0.1648
Black cherry	Natural	$(\exp(0.0109dbh/\exp(0.0429mean\_dbh\ ba)))-1$	0.1621
Bitternut hickory	Natural	$(\exp(0.021dbh\ mean\_dbh/\exp(0.2949mean\_dbh)))-1$	0.1085

Survival rate

Black spruce	Natural	$(1+(1/(\exp(-0.00051dbh^2+183.0/bal+26.3716dbh\_growth\_rate\ dbh))))^{-1}$	0.0062
Jack pine	Natural	$(1+(1/(\exp(-0.00069dbh^2+135.3/bal+8.3767dbh\_growth\_rate\ dbh))))^{-1}$	0.0073
Balsam fir	Natural	$(1+(1/(\exp(0.8038dbh+-0.0315bal+677.8dbh\_growth\_rate))))^{-1}$	9.02E-9
White spruce	Plantation	$(1+(1/(\exp(0.2273dbh+-0.2412bal+496.7dbh\_growth\_rate))))^{-1}$	0.0117
Trembling aspen	Natural	$(1+(1/(\exp(0.00952dbh^2+119.7/bal+285.6dbh\_growth\_rate^2))))^{-1}$	0.004
White birch	Natural	$(1+(1/(\exp(0.0142dbh^2+662.9dbh\_growth\_rate))))^{-1}$	1.11E-8
Sugar maple	Natural	$(1+(1/(\exp(9.8728dbh+65.5455/bal+26.7809dbh\_growth\_rate))))^{-1}$	2.65E-8
White pine	Natural	$(1+(1/(\exp(176.9/bal+1.0844dbh\_growth\_rate\ dbh))))^{-1}$	0.0091
Red pine	Natural	$(1+(1/(\exp(0.0639dbh^2+605.3/bal+51.2761dbh\_growth\_rate^2))))^{-1}$	2.65E-8
Red pine	Plantation	$(1+(1/(\exp(0.0168dbh^2+77.1451/bal+123.0dbh\_growth\_rate^2))))^{-1}$	0.0076
American beech	Natural	$(1+(1/(\exp(0.00609dbh\ bal+430.2/bal+1.5572dbh\_growth\_rate\ bal))))^{-1}$	0.0076
Balsam poplar	Natural	$(1+(1/(\exp(4.6209dbh+-0.0841bal+393.7dbh\_growth\_rate^2))))^{-1}$	3.59E-8

Height-dbh model

Black spruce	Natural	$32.3853((1-\exp(-0.0200dbh))^{1.0299})\ si^{0.2006}$	1.4124
Jack pine	Natural	$6.0237((1-\exp(-0.0601dbh))^{0.6449})\ si^{0.3941}\ ba^{0.0719}$	1.7281
Balsam fir	Natural	$(1-\exp(-0.1035dbh))\ (dbh\ ba)^{0.4373}$	2.2539
White spruce	Plantation	$(27.7353ba^{0.0931})\ ((1-\exp(-0.0310dbh))^{1.5241})$	1.4580
Trembling aspen	Natural	$(1-\exp(-0.1583dbh))\ ba^{0.3929}\ (si\ dbh)^{0.2676}$	1.8190
White birch	Natural	$10.1815(1-\exp(-0.0677dbh))\ si^{0.2824}$	1.5874
Sugar maple	Natural	$(0.8924qdbh)\ ((1-\exp(-0.0689dbh))^{1.2318})$	2.4770
White pine	Natural	$(26.2624ba^{0.1295})\ ((1-\exp(-0.0168dbh))^{0.7809})$	2.1377
Red pine	Natural	$(10.4580ba^{0.3511})\ ((1-\exp(-0.0395dbh))^{1.1475})$	2.1239
Red pine	Plantation	$(0.6980ba)\ ((1-\exp(-0.0619dbh))^{1.8594})$	2.0710
American beech	Natural	$(0.8867ba)\ ((1-\exp(-0.0647dbh))^{1.0707})$	3.2160
Yellow birch	Natural	$19.8091((1-\exp(-0.00153dbh^2))^{0.3354})$	2.7436
Basswood	Natural	$(1-\exp(-0.2011dbh))\ (dbh\ ba)^{0.4314}$	1.7571
Iron/Ash/Silver maple	Natural	$(ba^{0.9439})\ ((1-\exp(-0.0401dbh))^{0.7052})$	2.3657
Red oak	Natural	$24.8731((1-\exp(-0.0533dbh))^{1.1757})$	1.9667

Species group density index [§]

Species group			
Black spruce		$(0.0693prop\ ba^{2})/(exp\ (0.00337ba\ mean\_dbh))$	127.0
Jack pine		$-0.0074prop^{2}\ qdbh+8.5315ba+13.1703prop+0.1126prop^{2}$	156.5
White spruce		$((ba^{2}\ prop^{2})^{0.4785})+(-4.83E-6mean\_dbh\ prop^{2}\ ba^{2})$	228.6
Aspen		$-0.0119mean\_dbh\ prop^{2}+7.0235ba+0.2940prop^{2}$	183.0
White birch		$0.1929prop\ ba+-62.982qdbh+14.8358prop$	174.8
Red and White pine		$-0.00695prop^{2}\ mean\_dbh+0.000046ba^{2}\ prop^{2}+19.511prop$	247.5
Northern hardwoods		$-0.00091mean\_dbh\ prop^{2}+0.00114ba\ prop^{2}+4.4842prop$	109.2
Red oak		$-0.0103mean\_dbh\ prop^{2}+1.3357ba+0.3092prop^{2}$	22.5044

Small-tree models

Height growth rate

Black spruce	Natural	$-0.6337+((log(bal)ht)^{-0.0617})$	0.1095
Balsam fir	Natural	$(exp(0.0108ht\ log(bal)+log(bal)^{-2.6830}))-1$	0.0893
White spruce	Plantation	$0.2351+0.1435ht+-0.0241ht^{2}+-0.0192bal$	0.1079
White pine	Natural	$(exp(0.0704log(ht)^{2}+-0.00233ht\ bal+0.0180log(bal)^{2}))-1$	0.0903

dbh growth rate

Black spruce	Natural	$0.6944+0.0838dbh+-0.00942dbh^{2}+-0.2548log(bal)$	0.1253
Balsam fir	Natural	$0.1683log(dbh)+-0.0001bal^{2}$	0.1080
White spruce	Plantation	$0.7164+0.0165dbh+-0.2132log(bal)$	0.1453
White pine	Natural	$dbh^{-3.0397}+bal^{-0.8391}$	0.0779

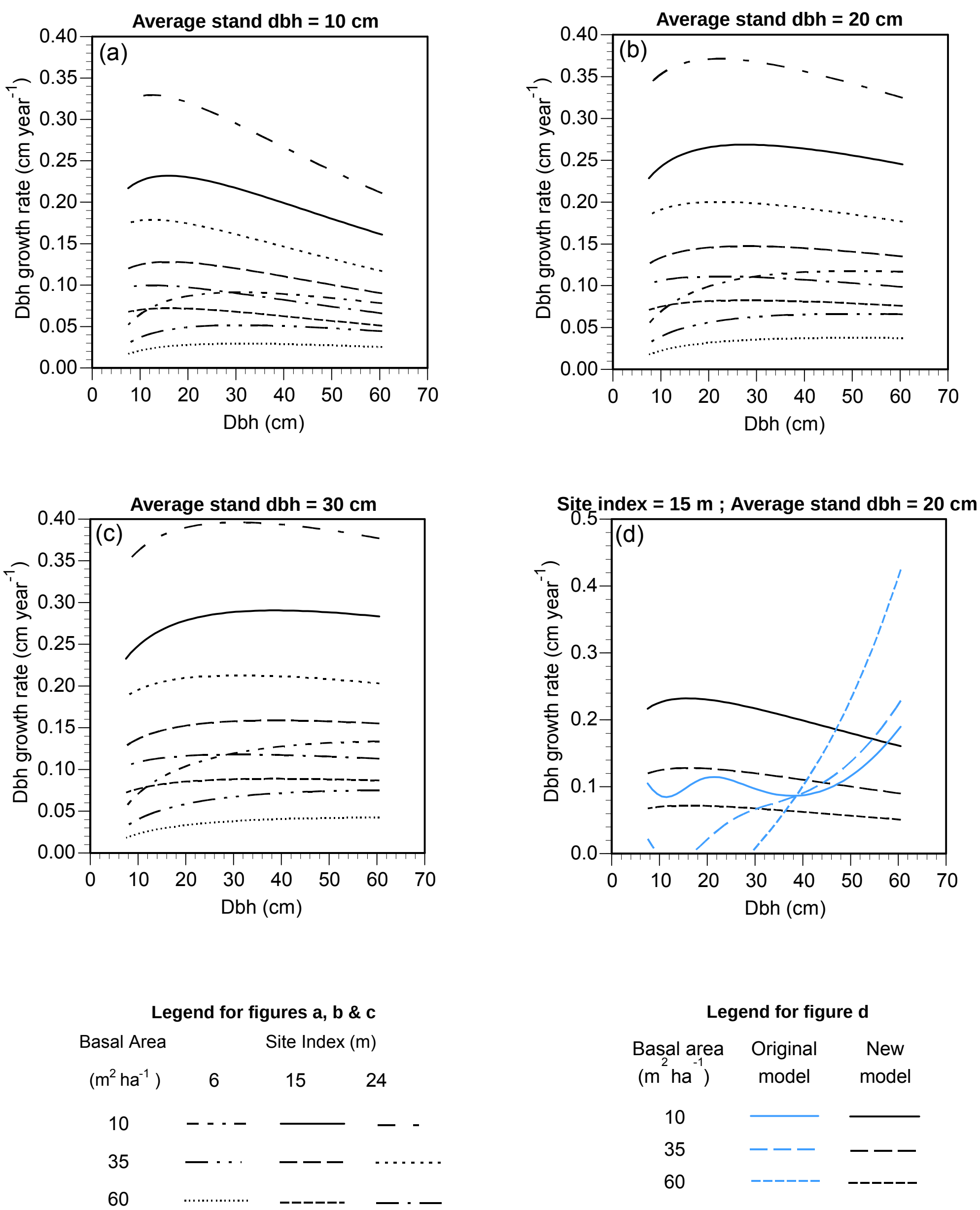
*Legend

dbh	Diameter at breast height (cm)
si	Site index (m)
mean_dbh	Average stand dbh (cm)
ba	Basal area (m^2 ha^{-1})
bal	Basal area of the trees greater than the subject tree (m^2 ha^{-1})
dbh_growth_rate	Annual dbh increment rate (cm yr^{-1})
ht	Stem height-1.3 (m)
qdbh	Quadratic mean diameter (cm)
prop	Species percentage based on number of trees per ha (%)
age	Age (yr)

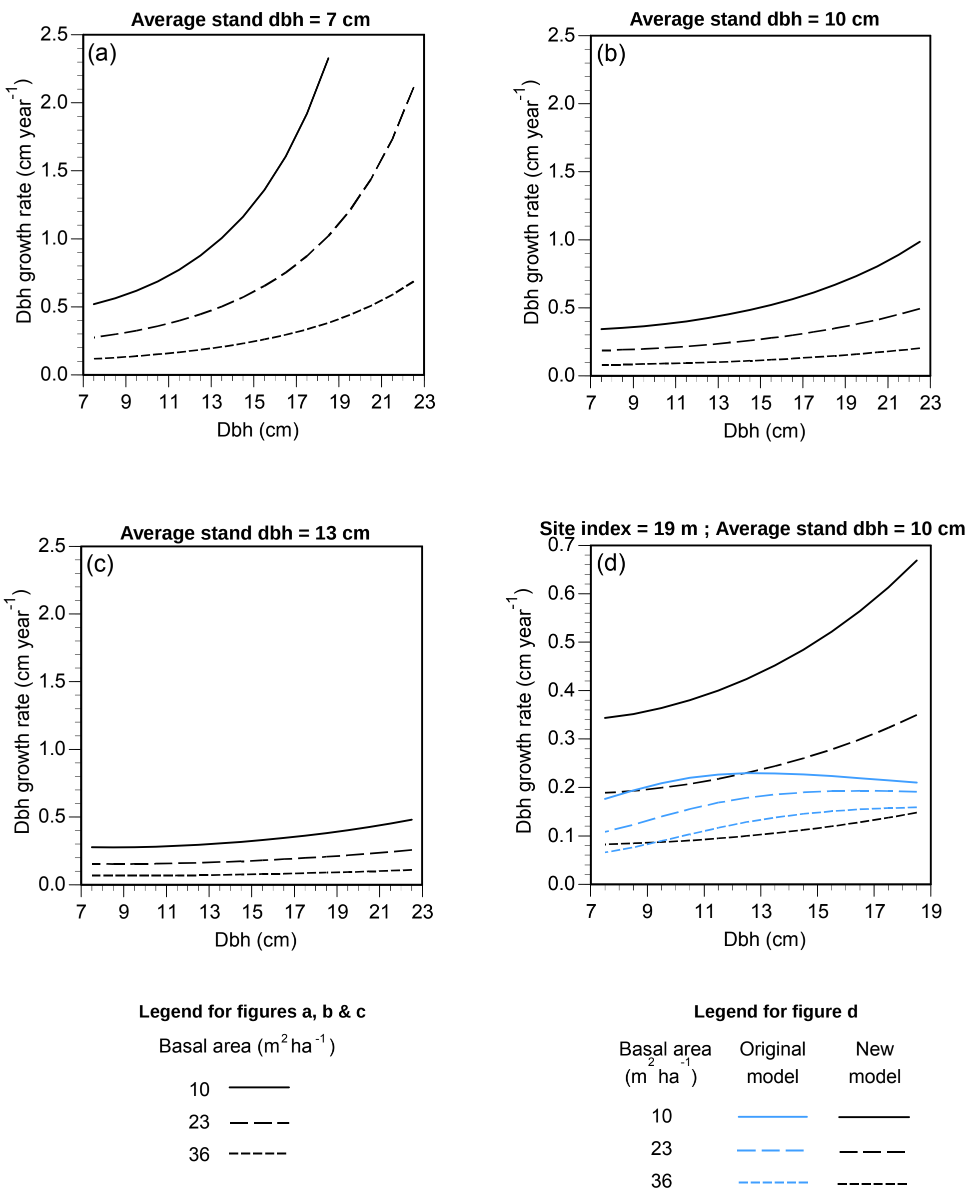
§Stand density (number of trees per ha) for the species included in each of the following groups of species.

Species group	Species
Black spruce	Black spruce, Balsam fir and Tamarack
Jack pine	Jack pine
White spruce	White spruce, White cedar and Cedar all
Aspen	Trembling aspen, Balsam poplar, Striped maple
White birch	White birch
Red and White pine	Red pine, White pine
Northern hardwood	Black ash, Silver maple, Black cherry, Elm all, Yellow birch, Basswood, Sugar maple, American beech, White ash and Bitternut hickory
Red oak	Red oak and Ironwood

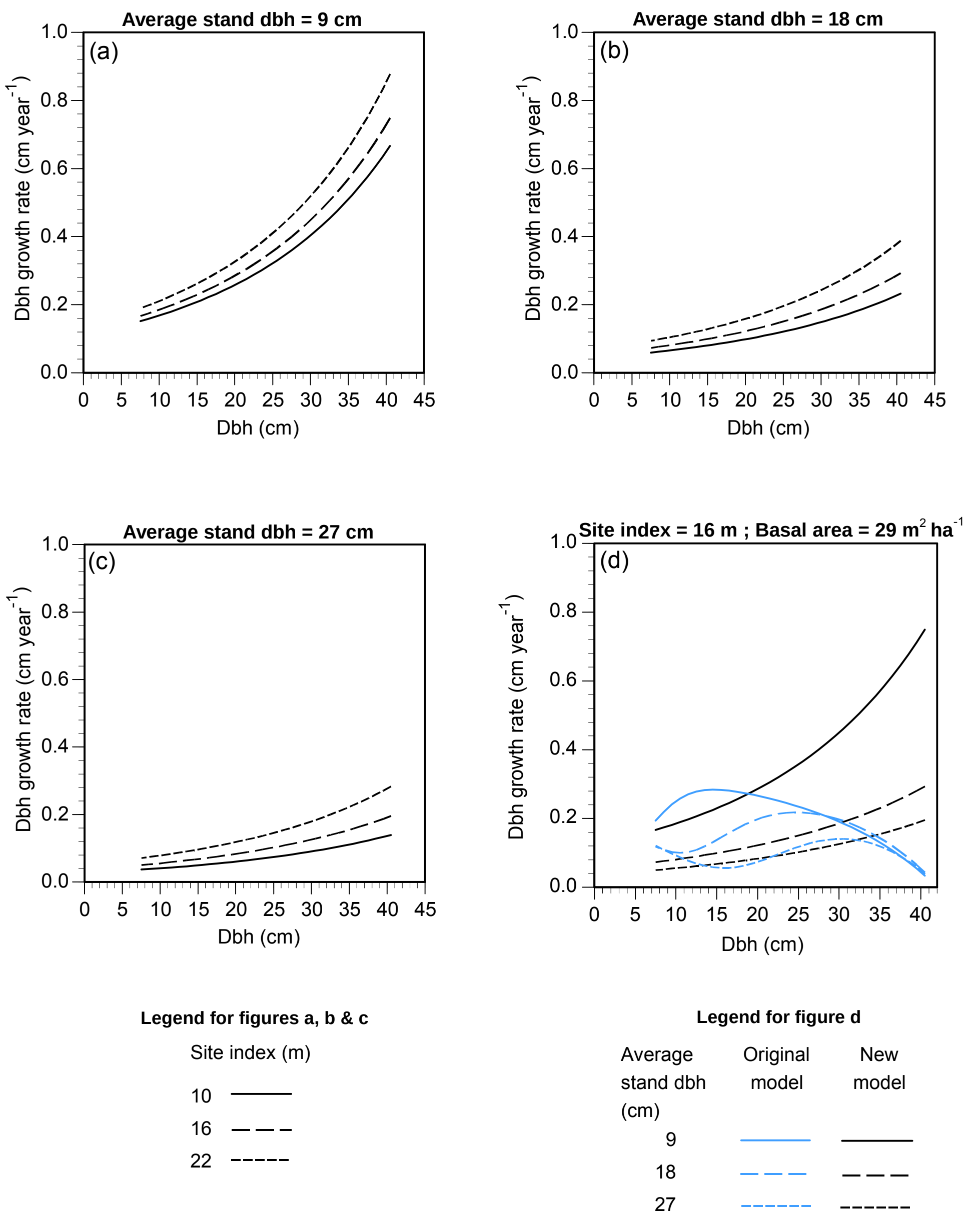
Appendix 3. Biological consistency analysis for dbh growth rate models



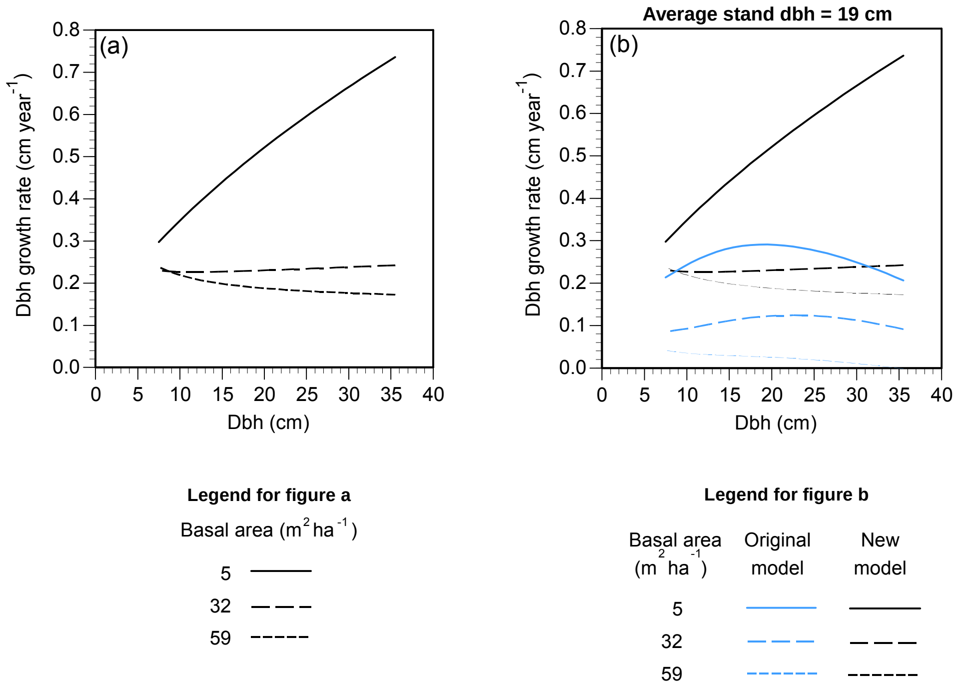
Appendix 3.1: Predicted dbh growth rate for black spruce in natural stands as a function of dbh for different conditions of basal area, site index and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



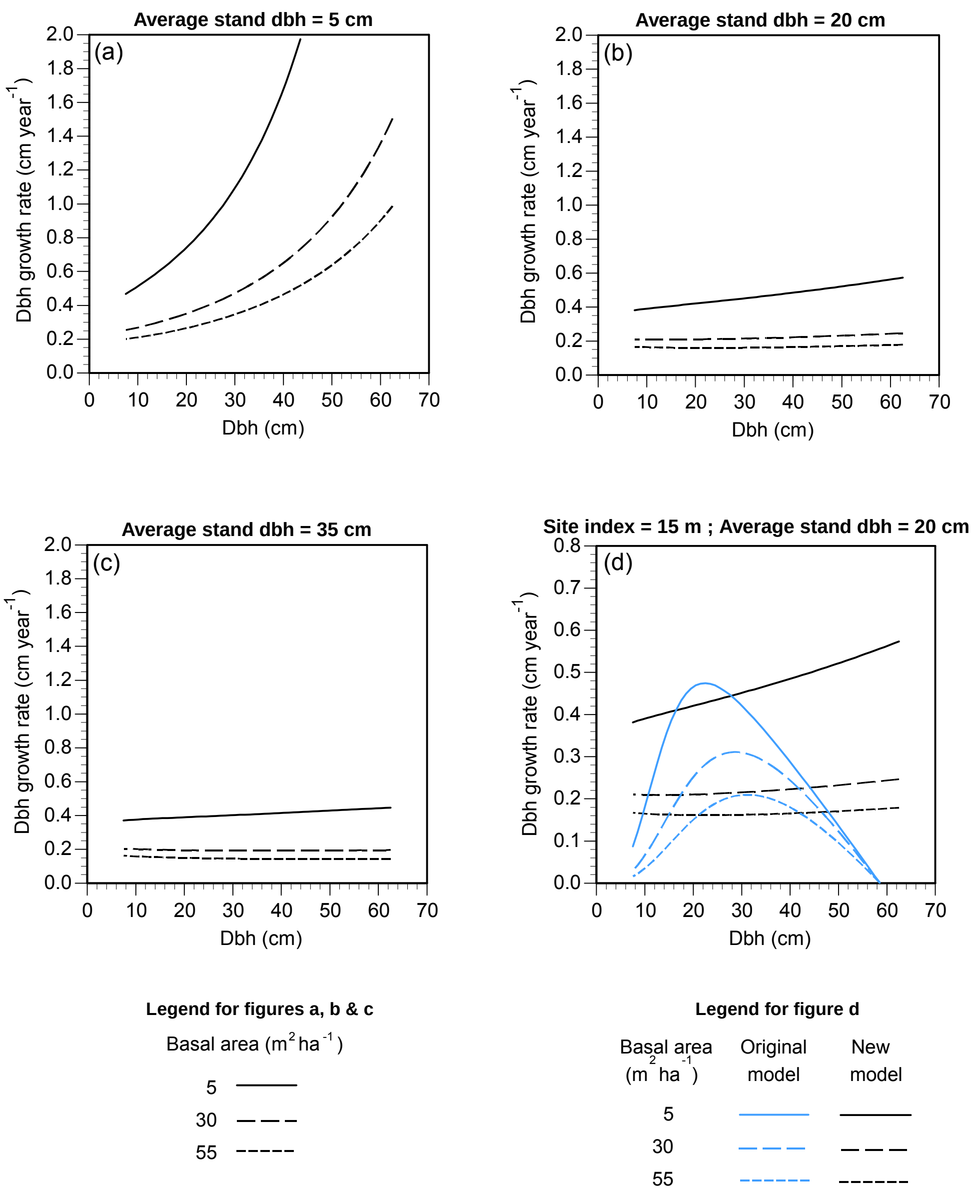
Appendix 3.2: Predicted dbh growth rate for planted black spruce as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



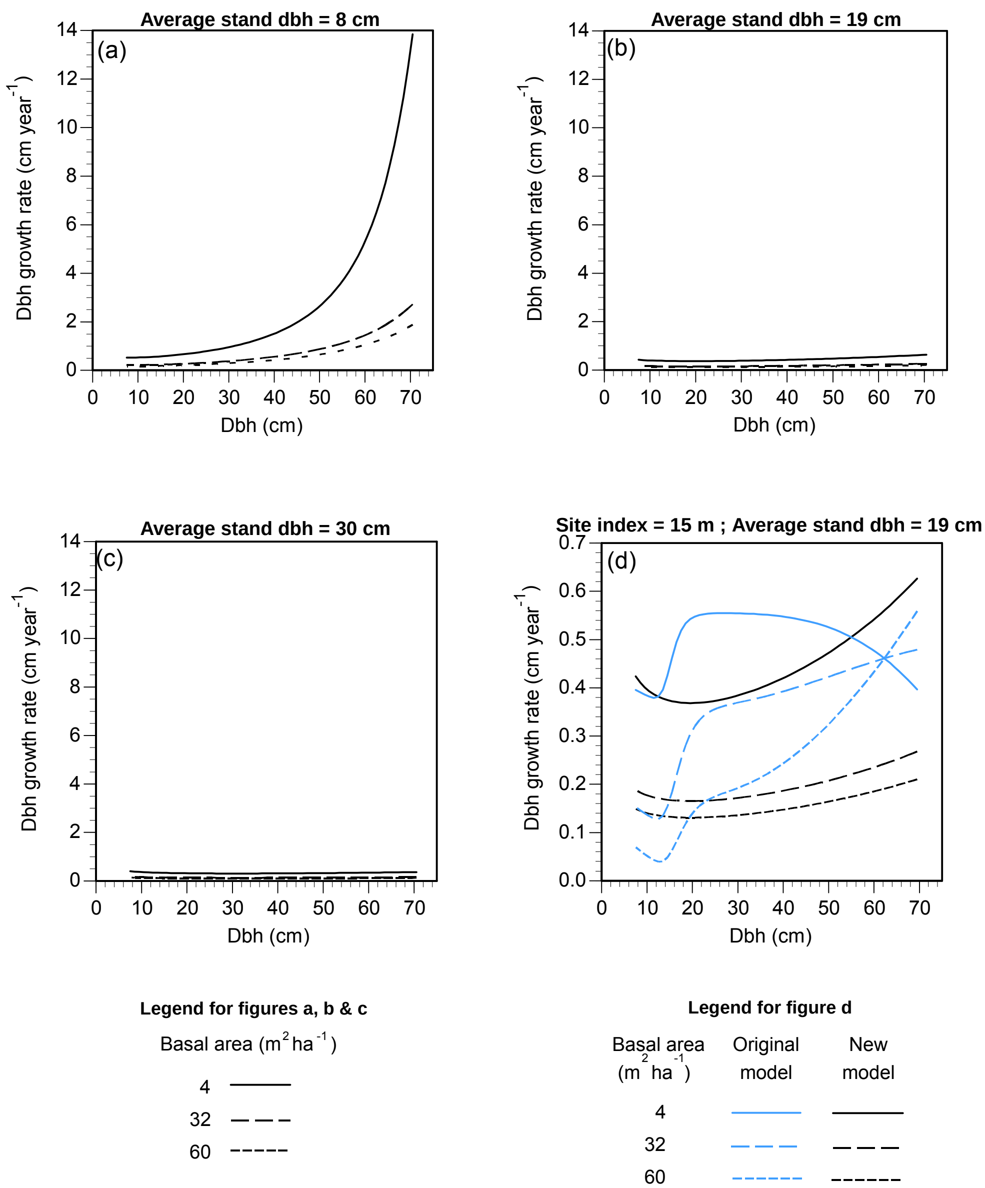
Appendix 3.3: Predicted dbh growth rate for jack pine in natural stands as a function of dbh for different conditions of site index and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



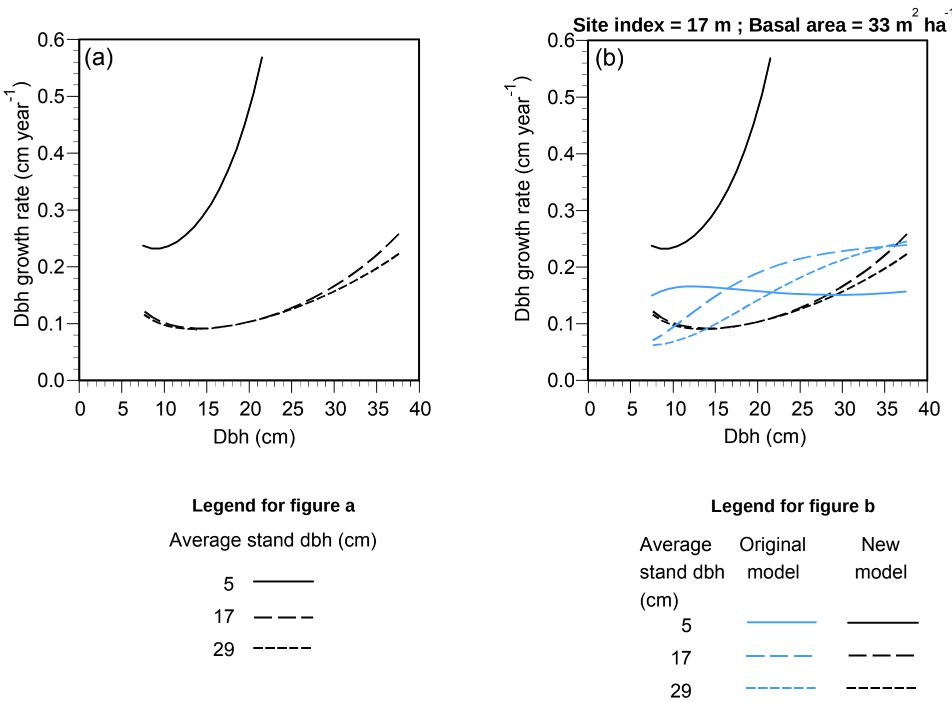
Appendix 3.4: Predicted dbh growth rate for balsam fir in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



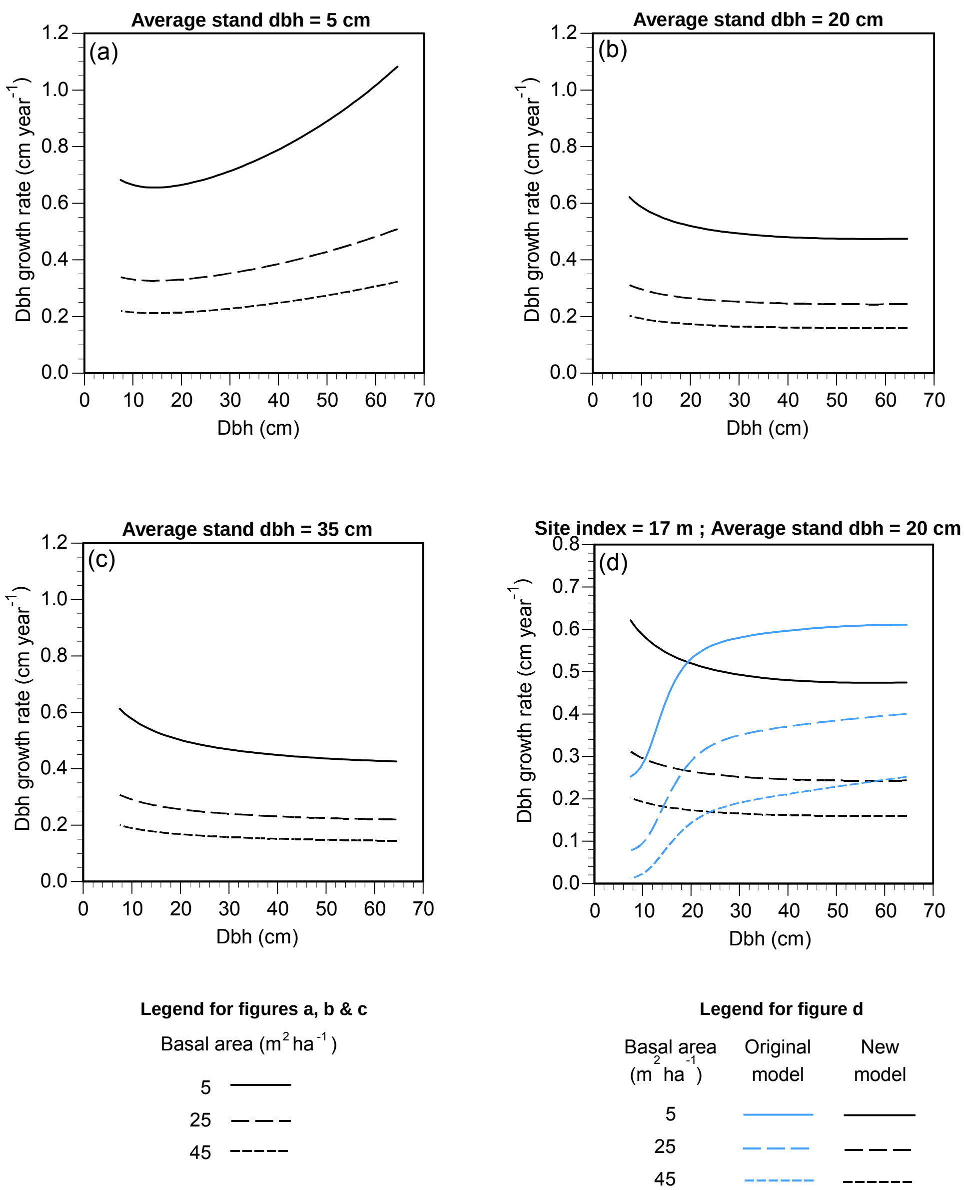
Appendix 3.5: Predicted dbh growth rate for planted white spruce as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



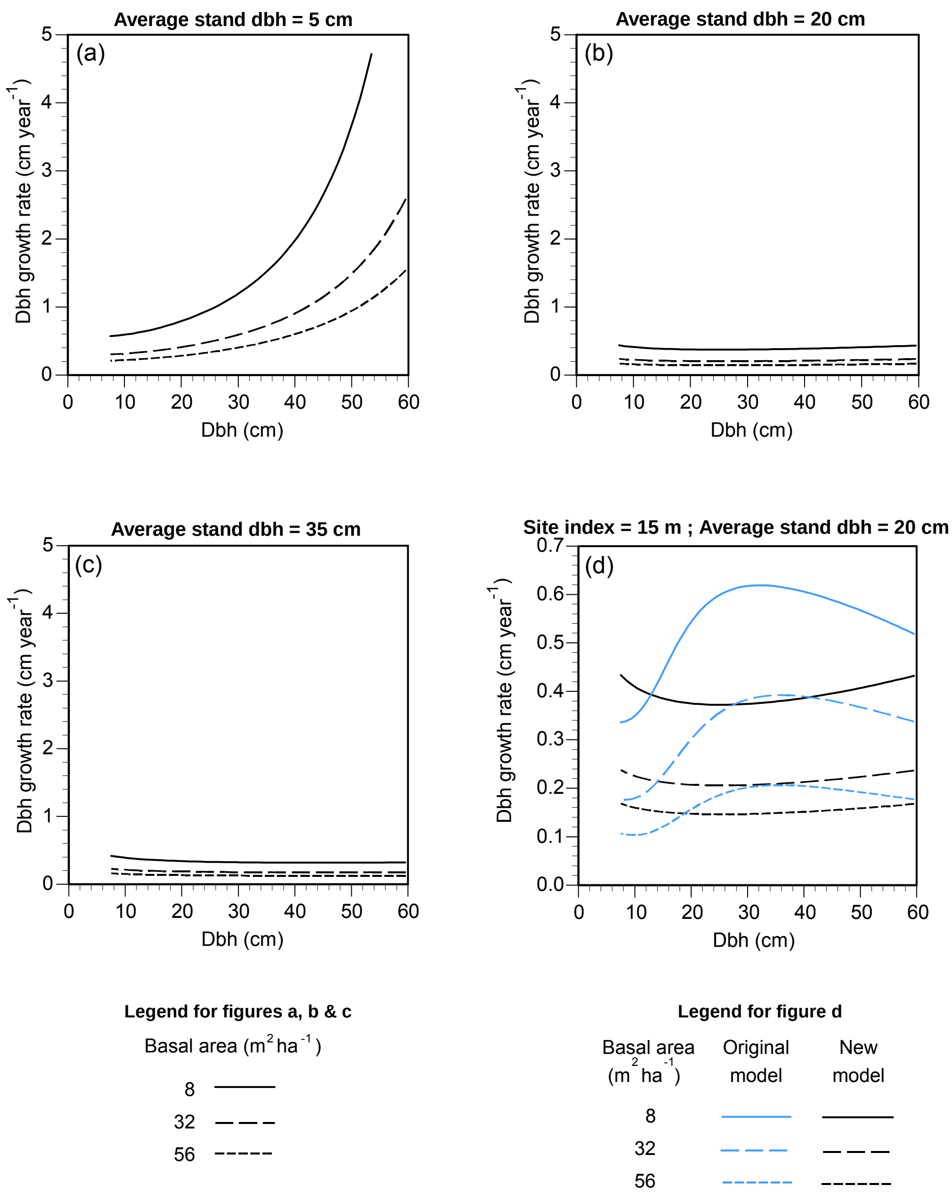
Appendix 3.6: Predicted dbh growth rate for trembling aspen in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



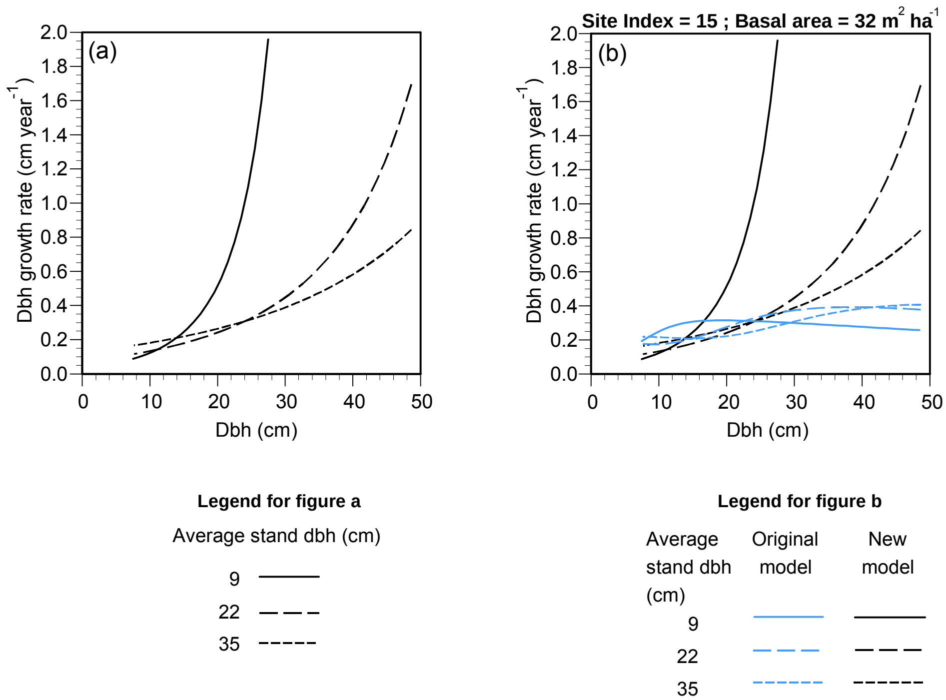
Appendix 3.7: Predicted dbh growth rate for white birch in natural stands as a function of dbh for different conditions of average stand dbh using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



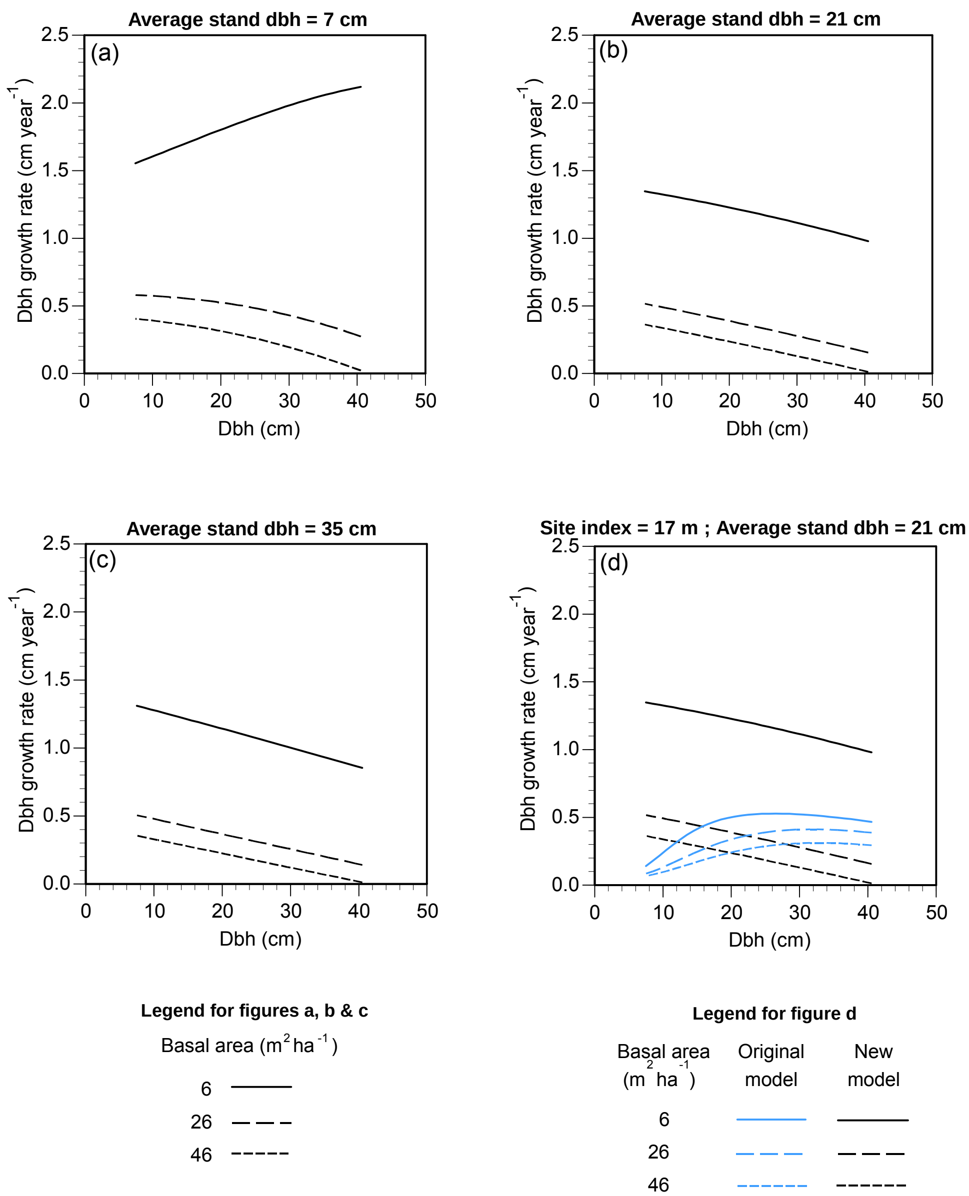
Appendix 3.8: Predicted dbh growth rate for sugar maple in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



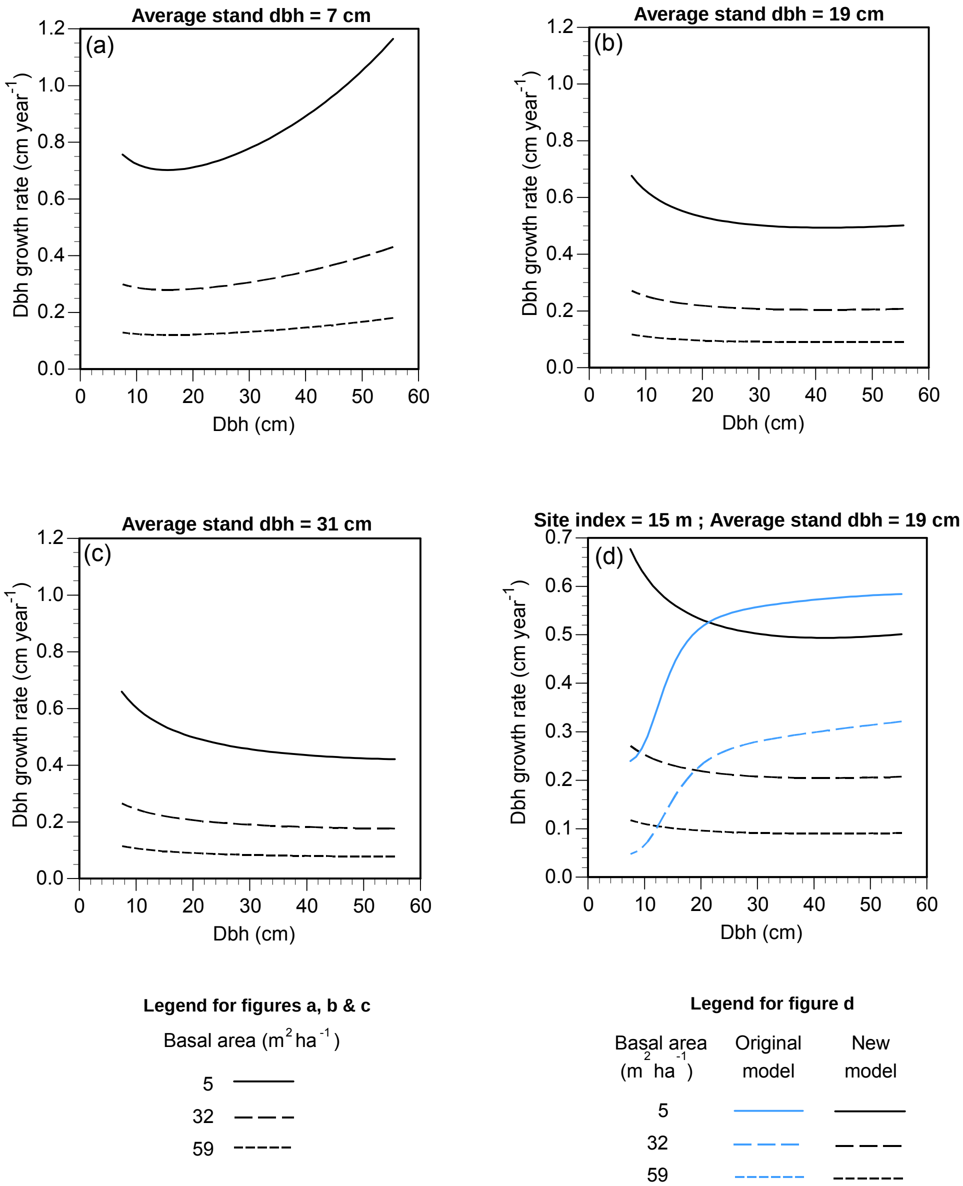
Appendix 3.9: Predicted dbh growth rate for white pine in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



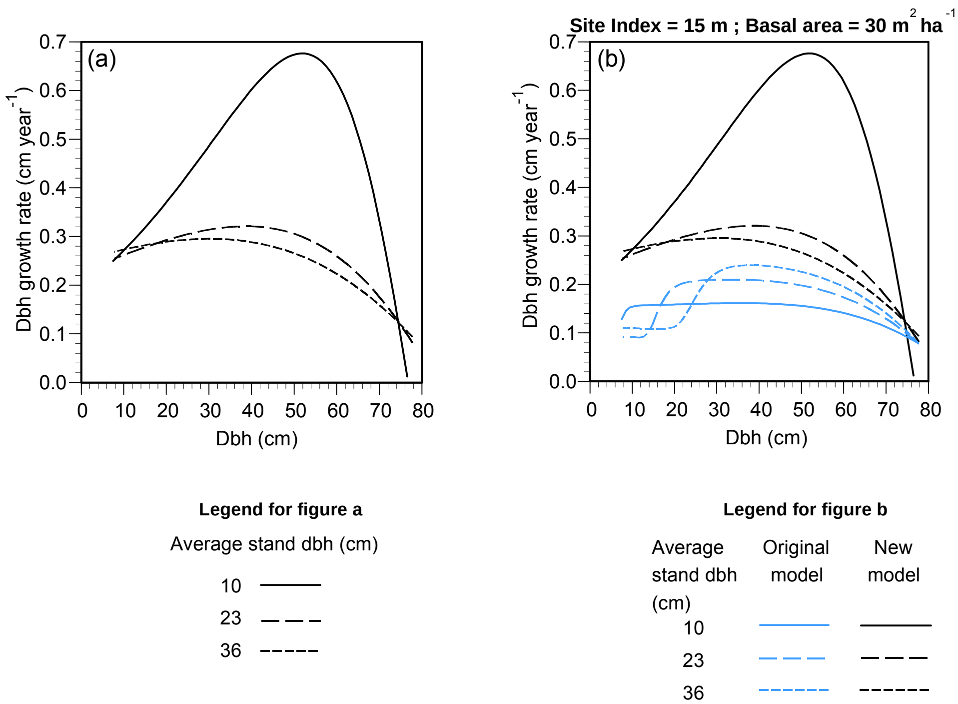
Appendix 3.10: Predicted dbh growth rate for planted white pine as a function of dbh for different conditions of average stand dbh using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



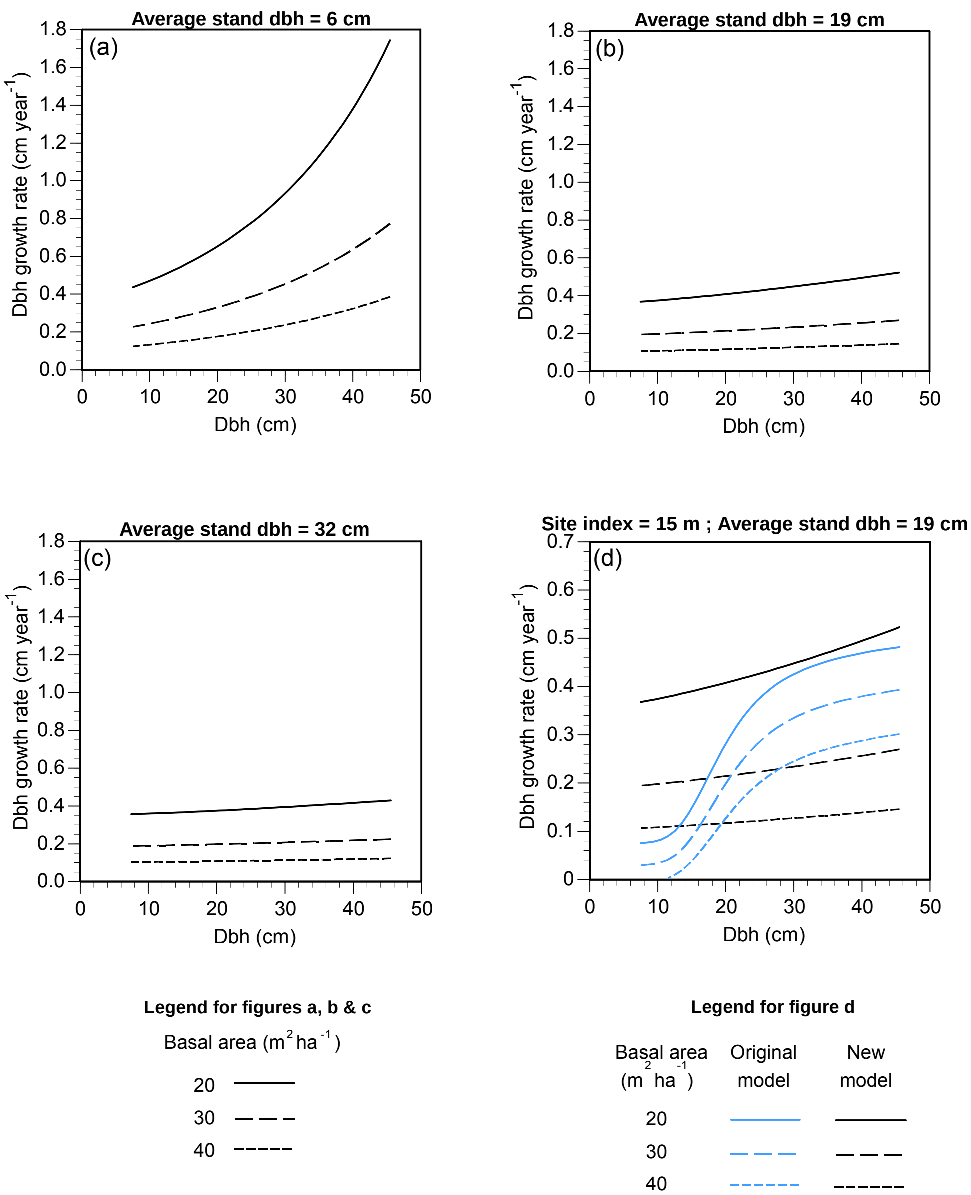
Appendix 3.11: Predicted dbh growth rate for planted red pine as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



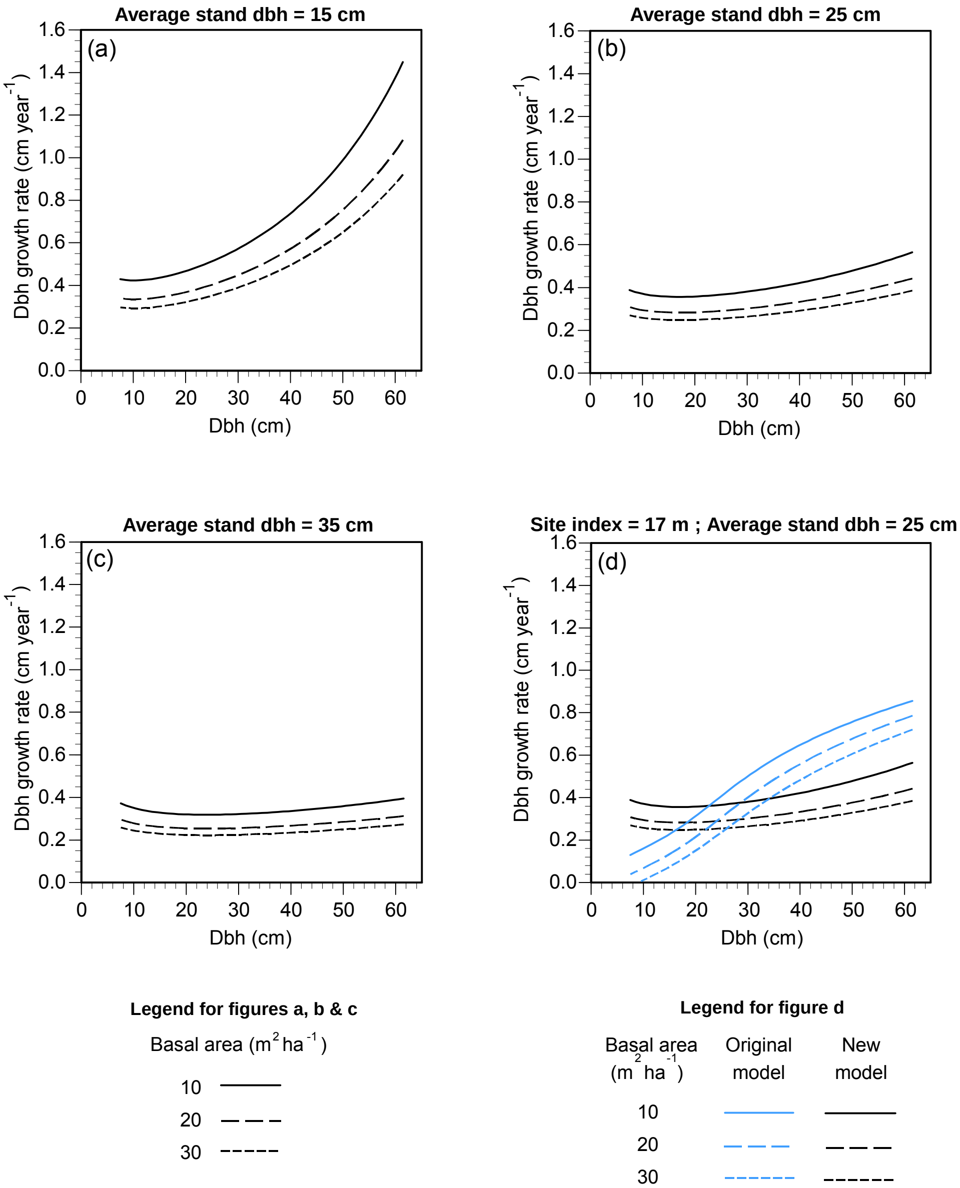
Appendix 3.12: Predicted dbh growth rate for American beech in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



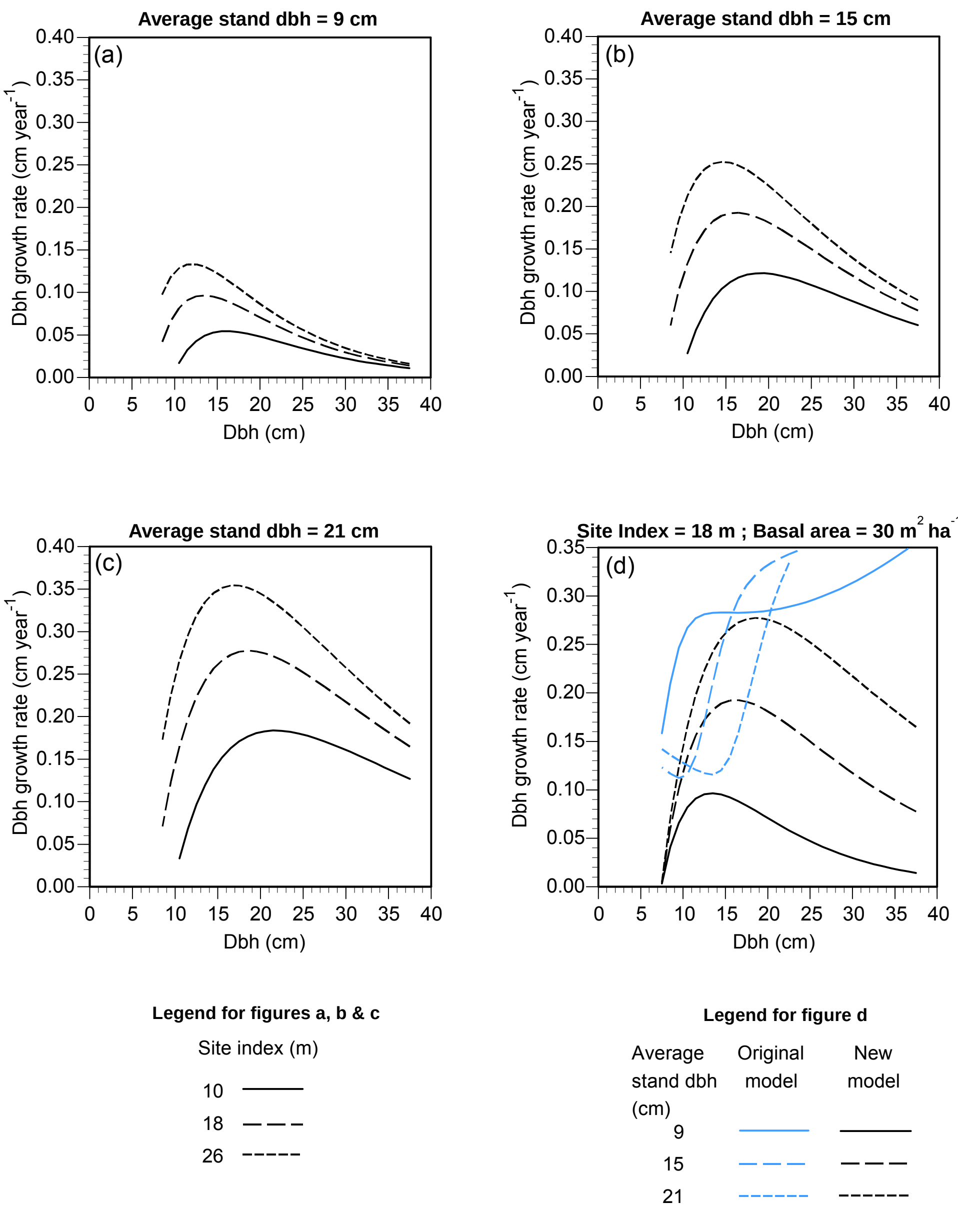
Appendix 3.13: Predicted dbh growth rate for yellow birch in natural stands as a function of dbh for different conditions of average stand dbh using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



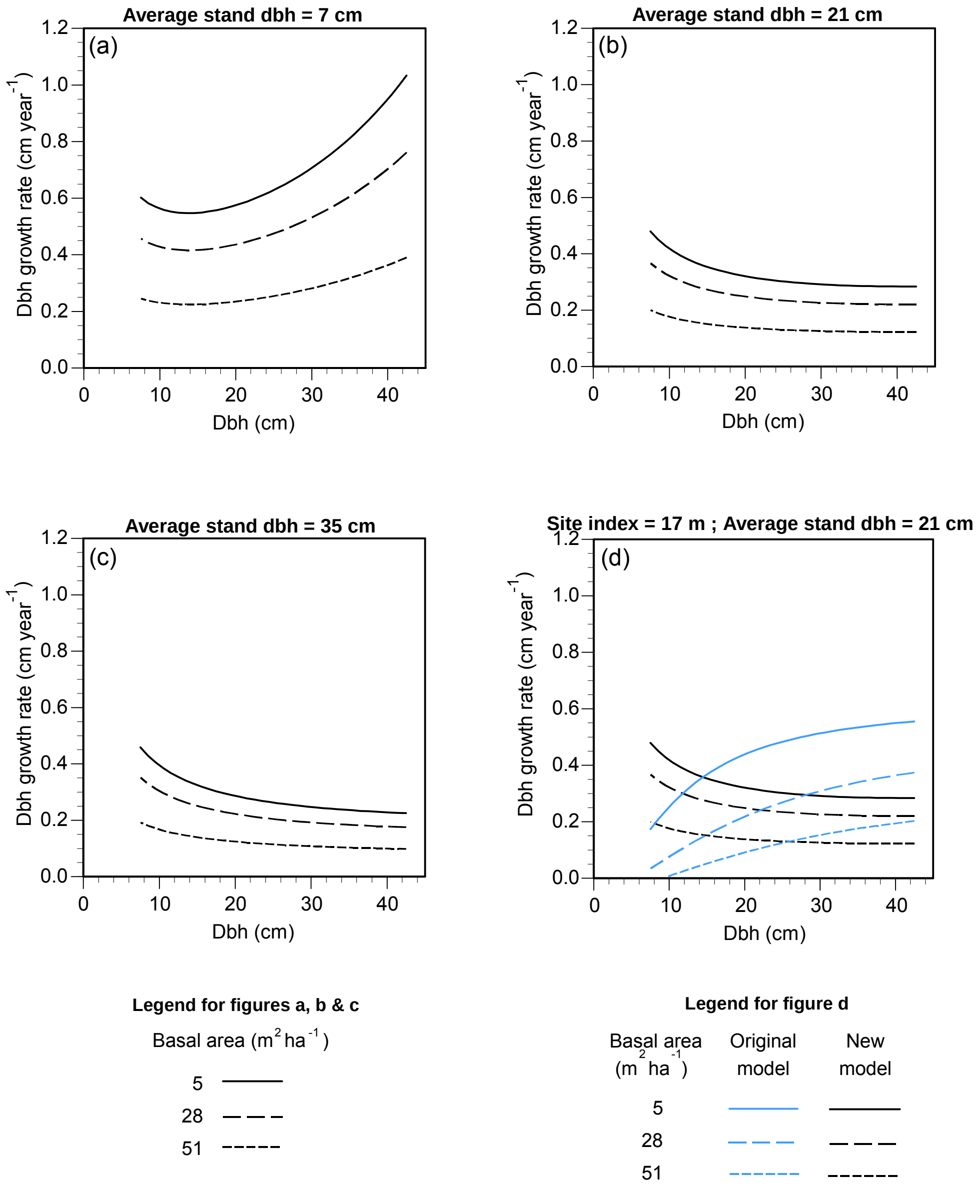
Appendix 3.14: Predicted dbh growth rate for basswood in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



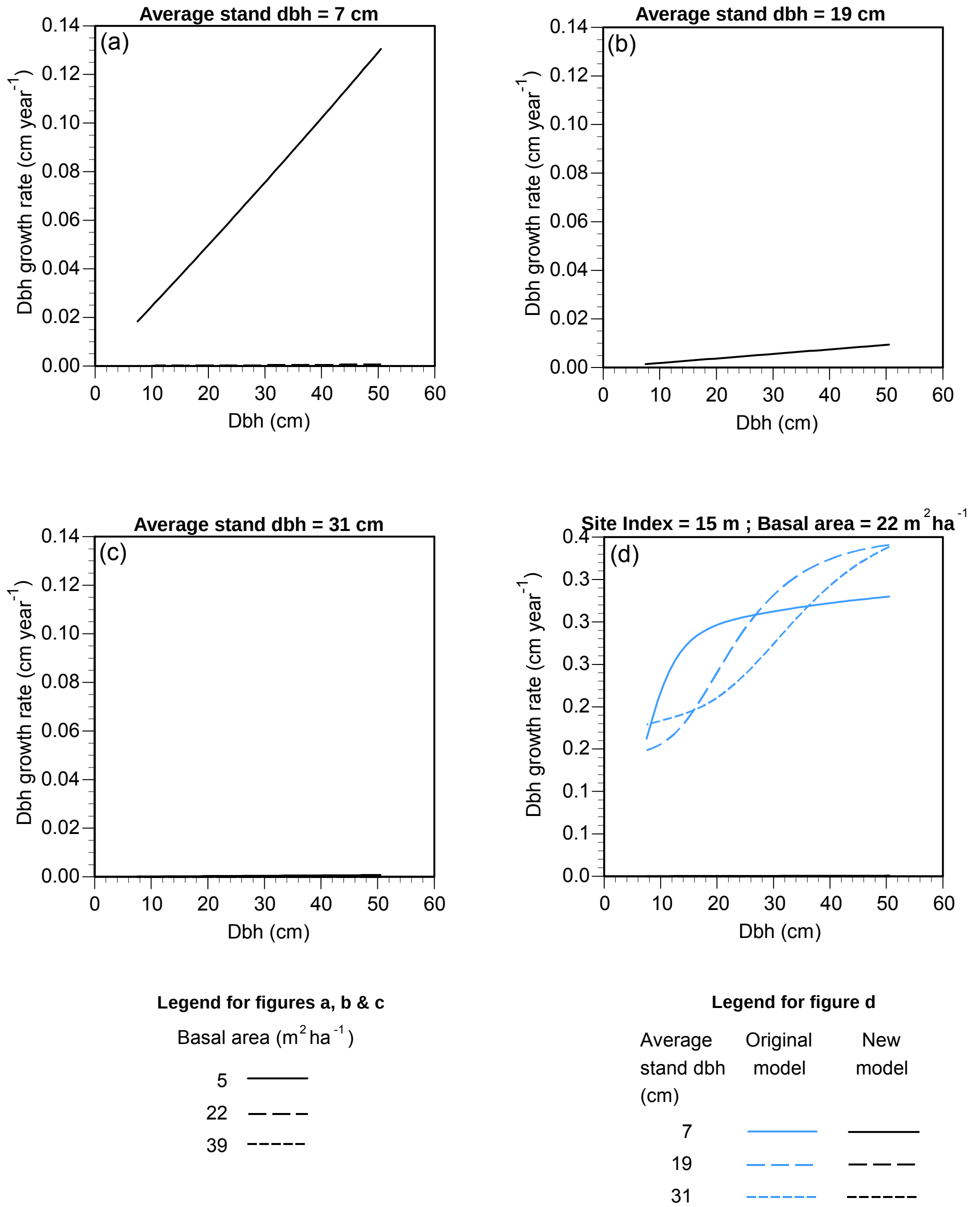
Appendix 3.15: Predicted dbh growth rate for silver maple in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



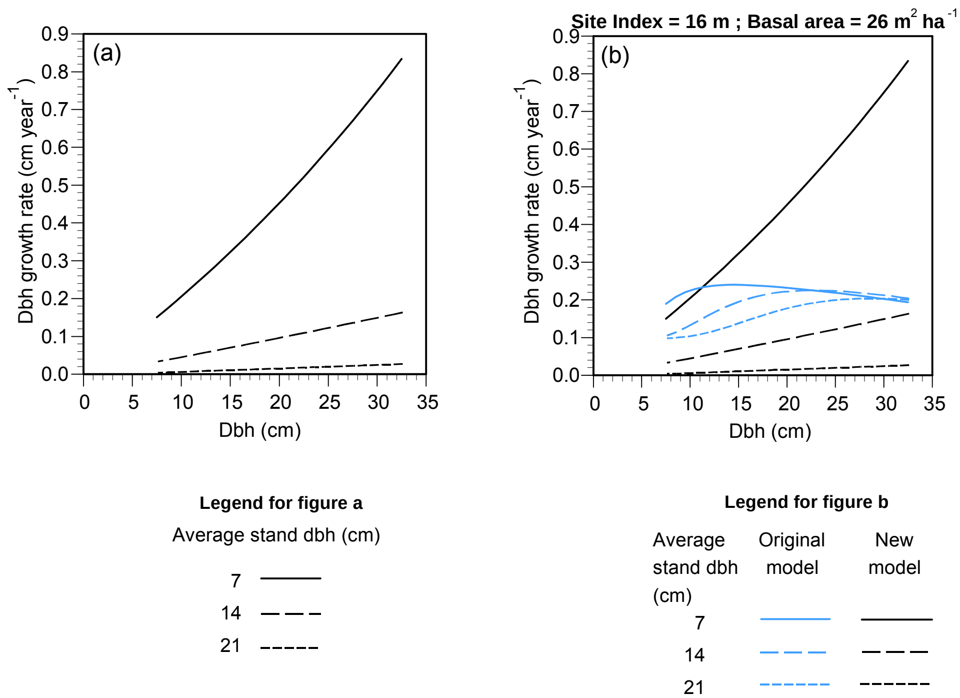
Appendix 3.16: Predicted dbh growth rate for balsam poplar in natural stands as a function of dbh for different conditions of site index and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



Appendix 3.17: Predicted dbh growth rate for red oak in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).

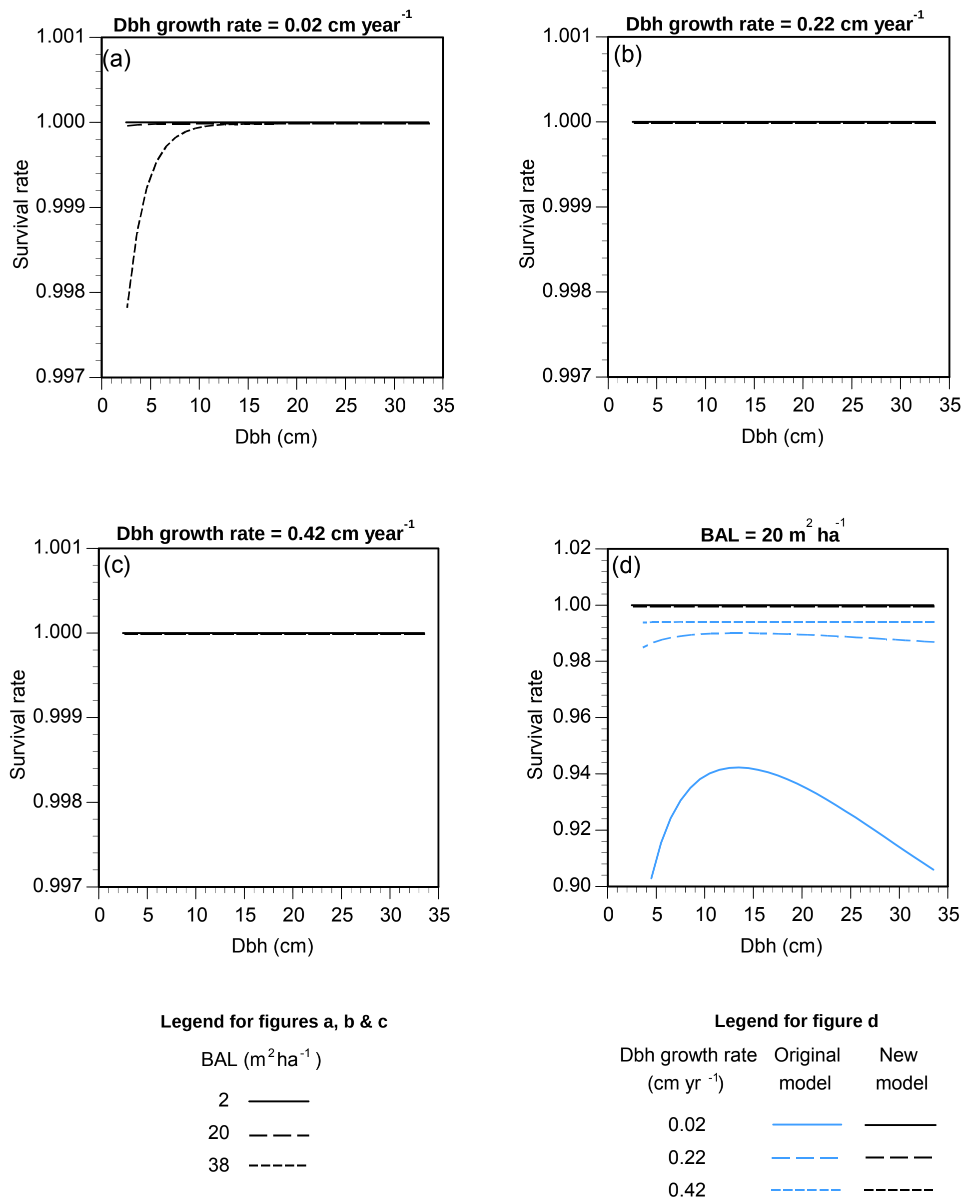


Appendix 3.18: Predicted dbh growth rate for black cherry in natural stands as a function of dbh for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).

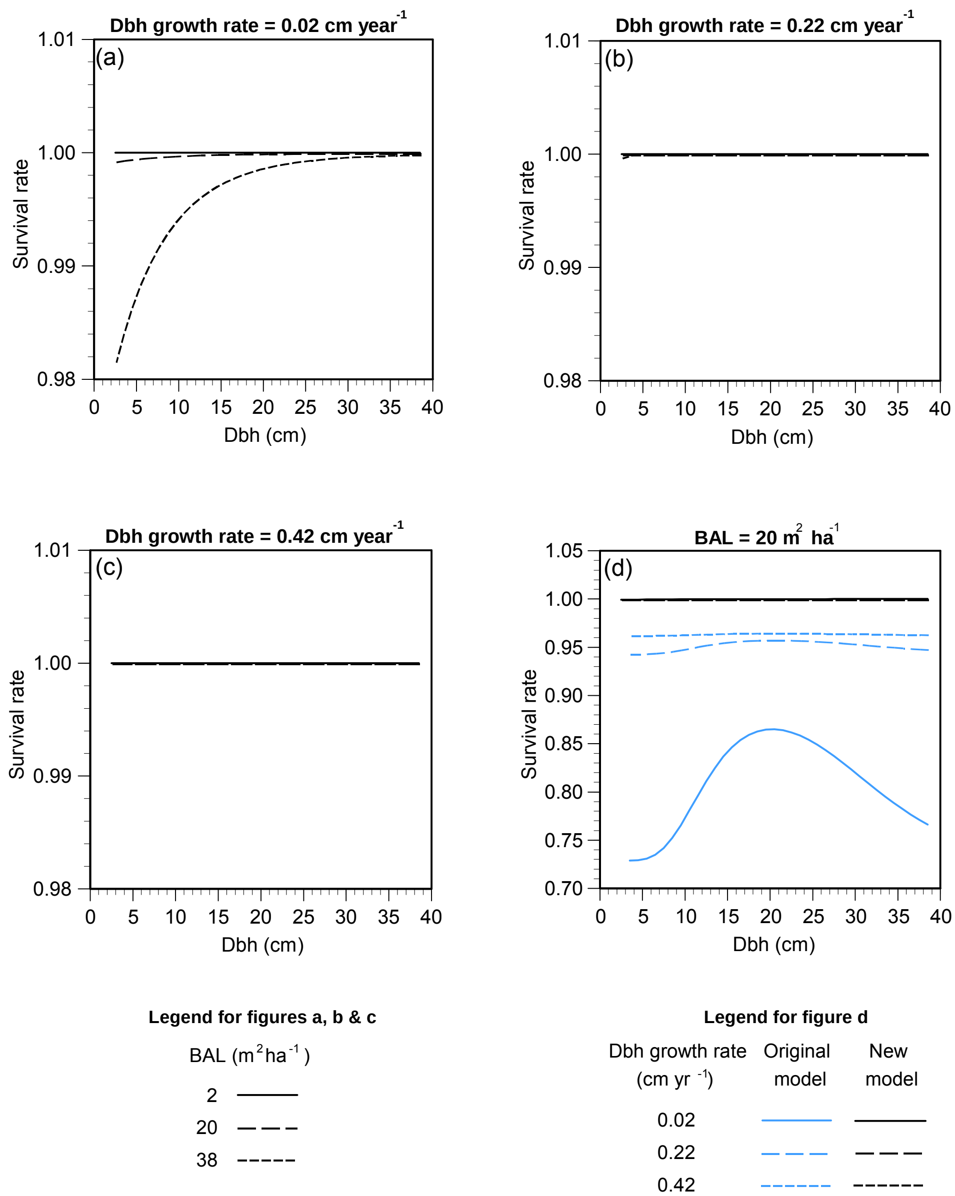


Appendix 3.19: Predicted dbh growth rate for hickory in natural stands as a function of dbh for different conditions of average stand dbh using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).

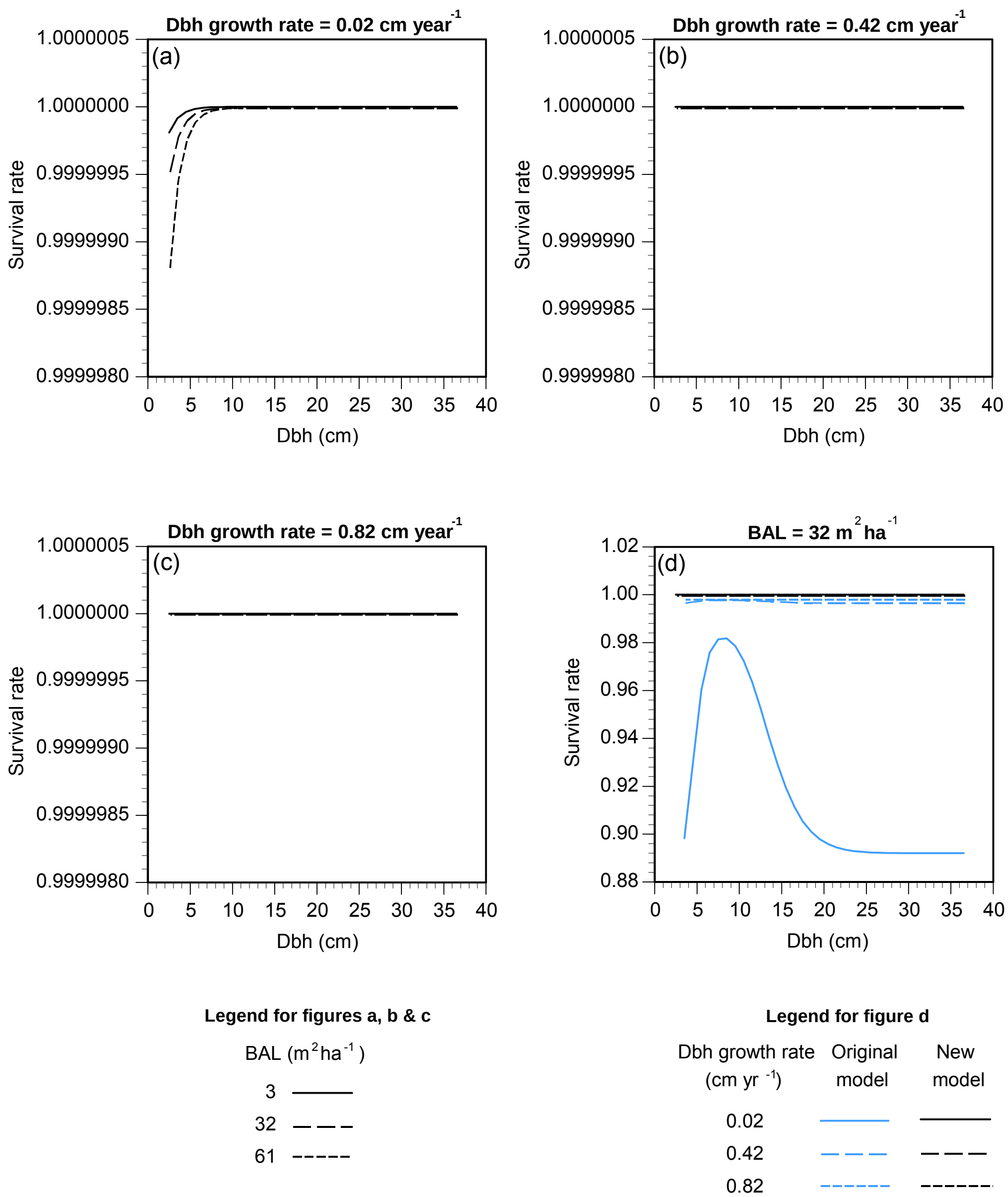
Appendix 4. Biological consistency analysis for survival rate models



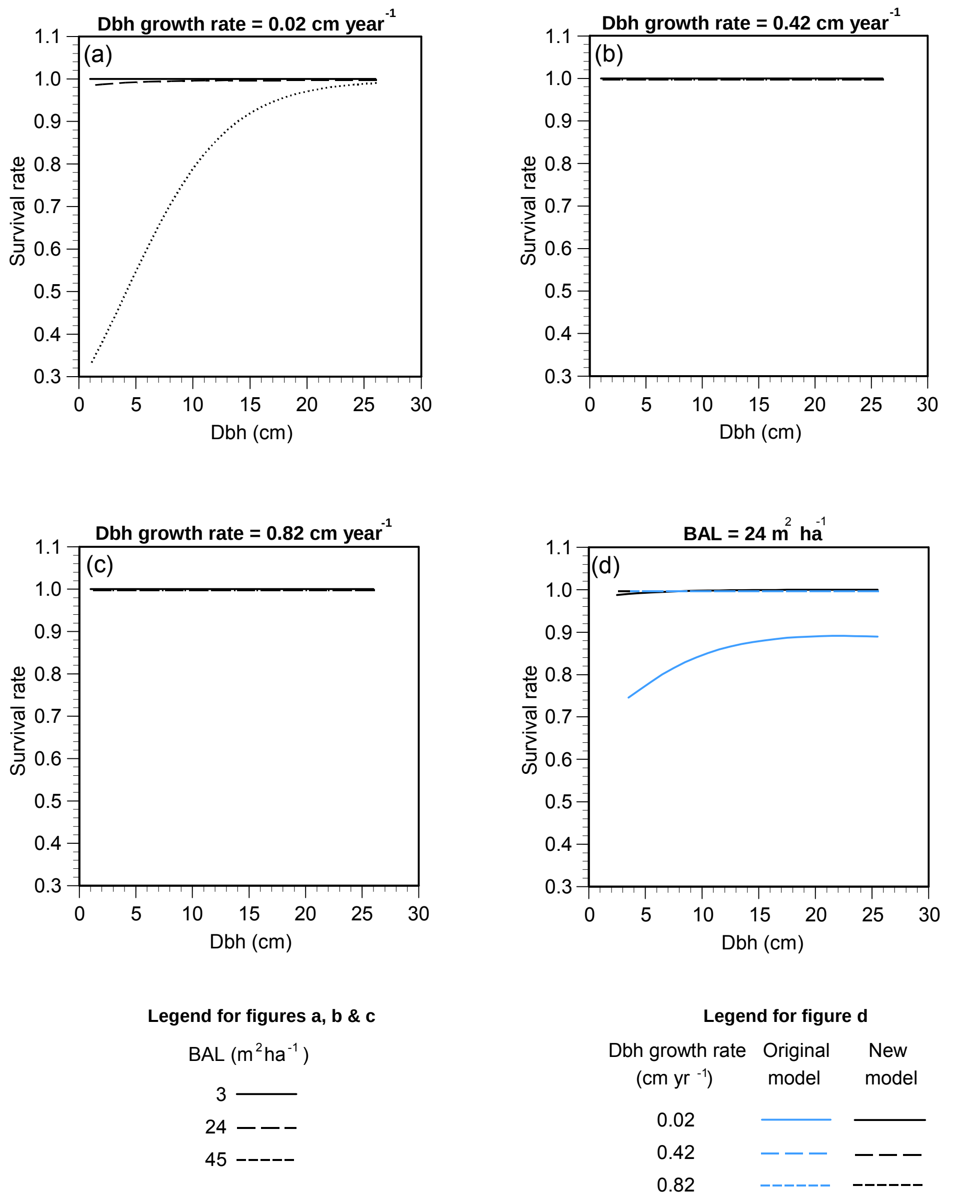
Appendix 4.1: Predicted survival rate for black spruce in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



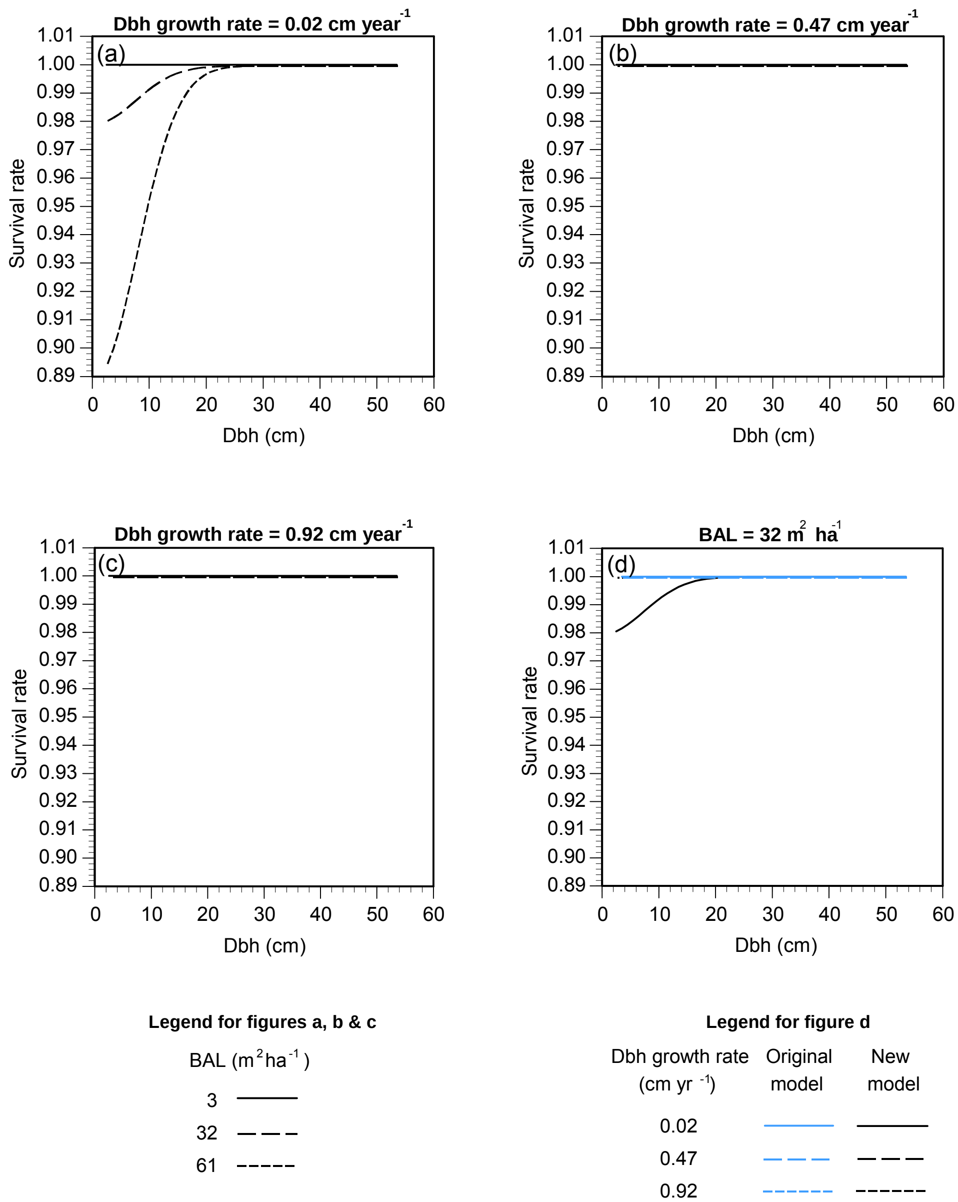
Appendix 4.2: Predicted survival rate for jack pine in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



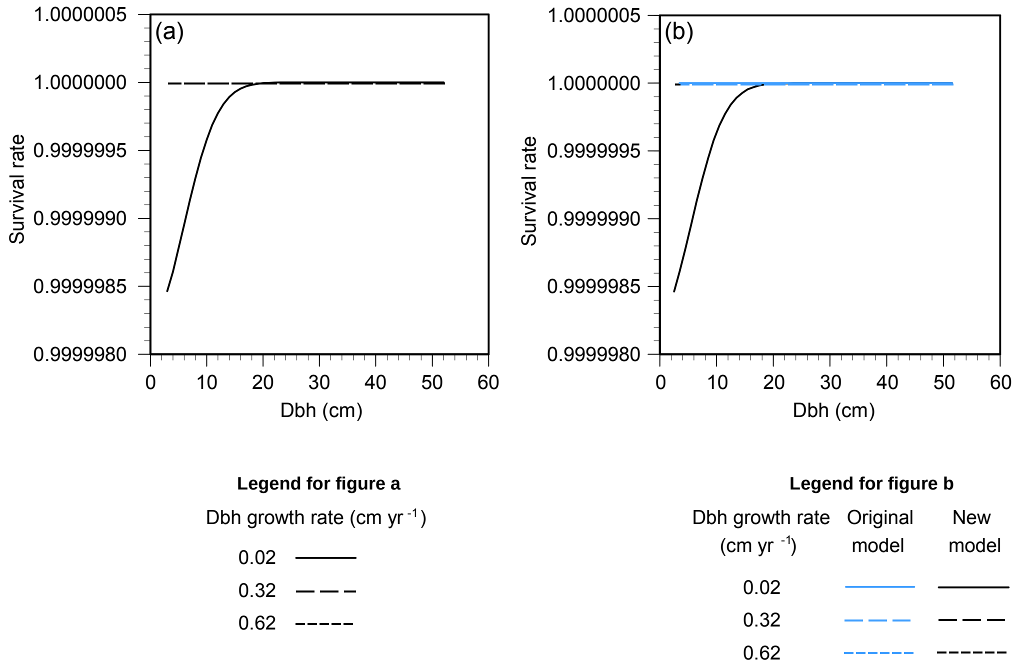
Appendix 4.3: Predicted survival rate for balsam fir in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



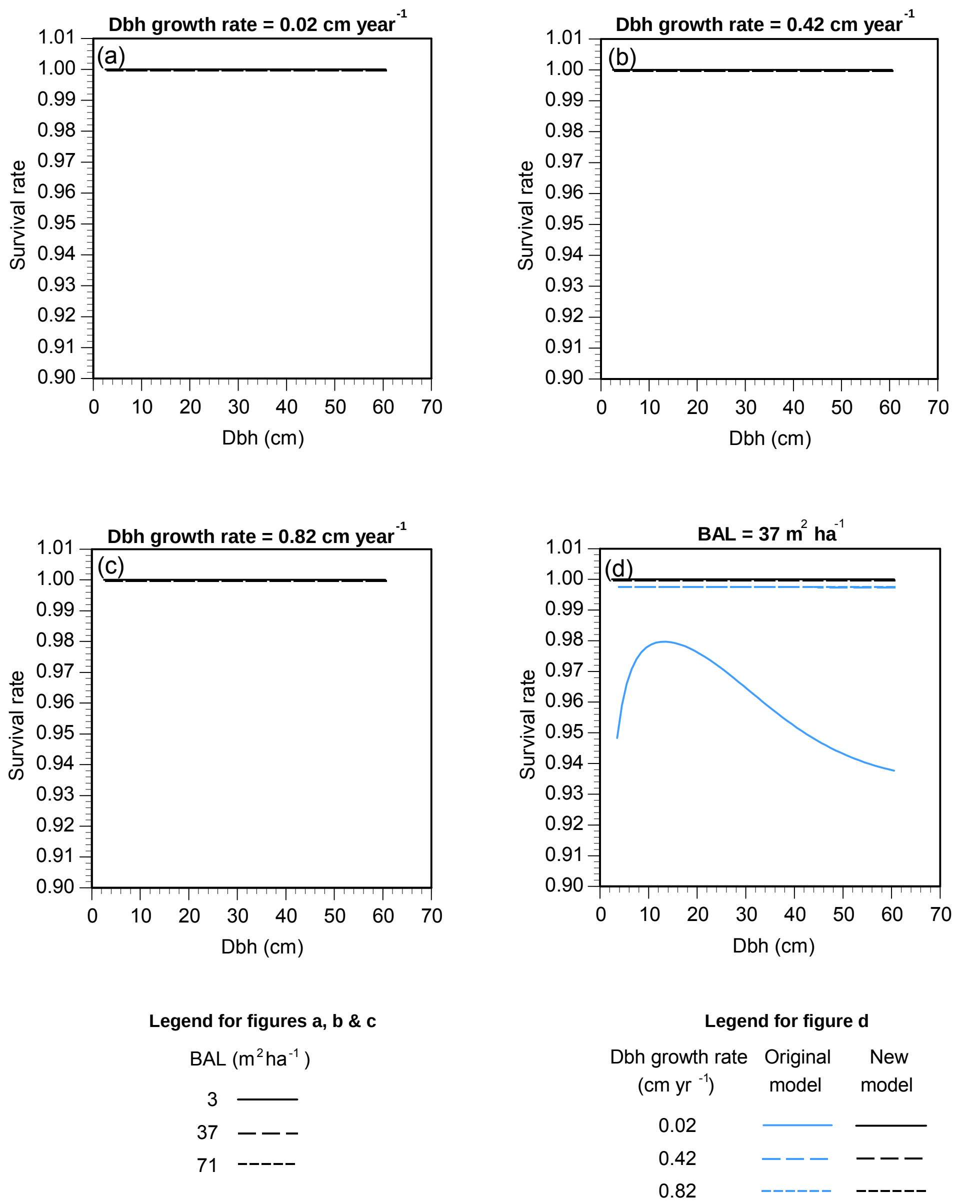
Appendix 4.4: Predicted survival rate for planted white spruce as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



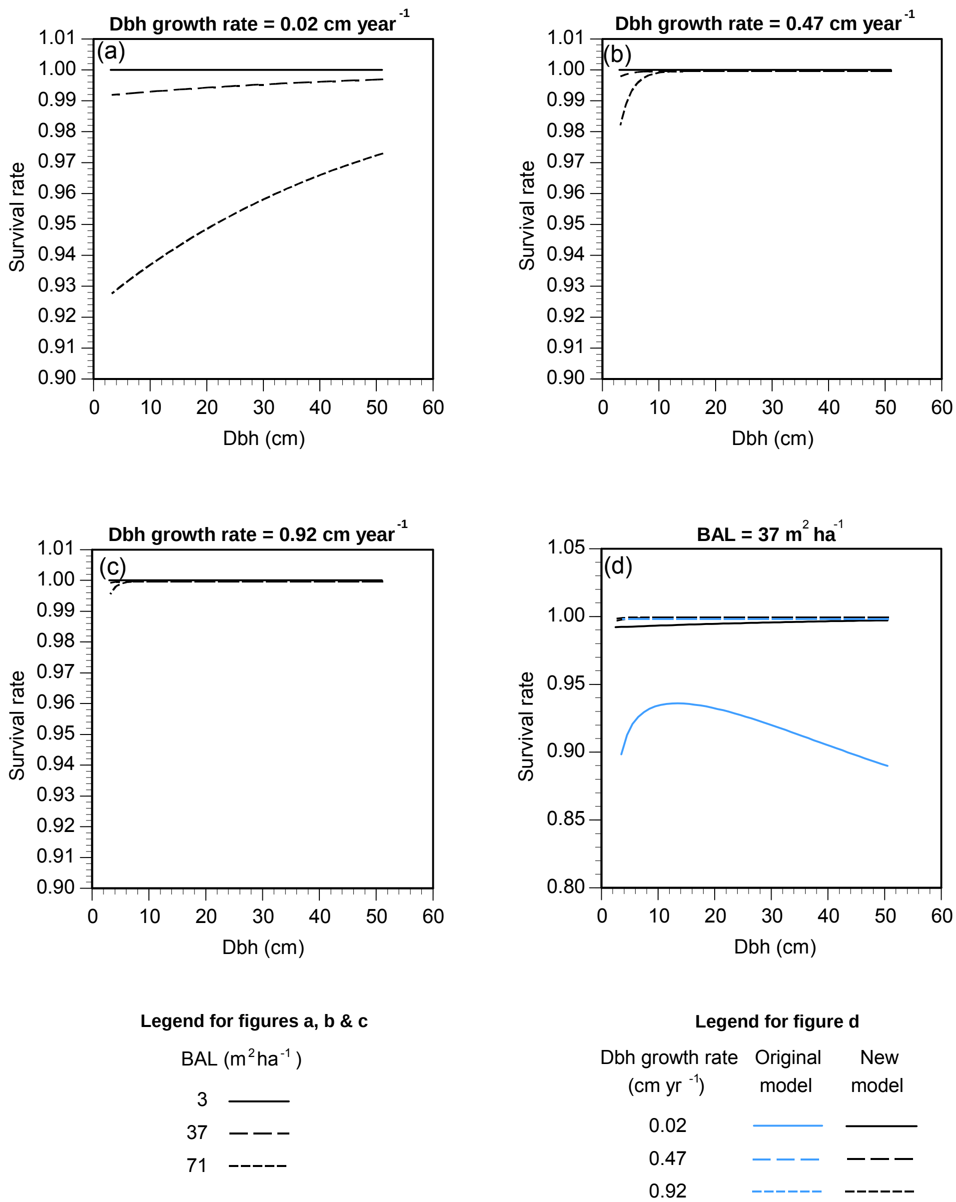
Appendix 4.5: Predicted survival rate for trembling aspen in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



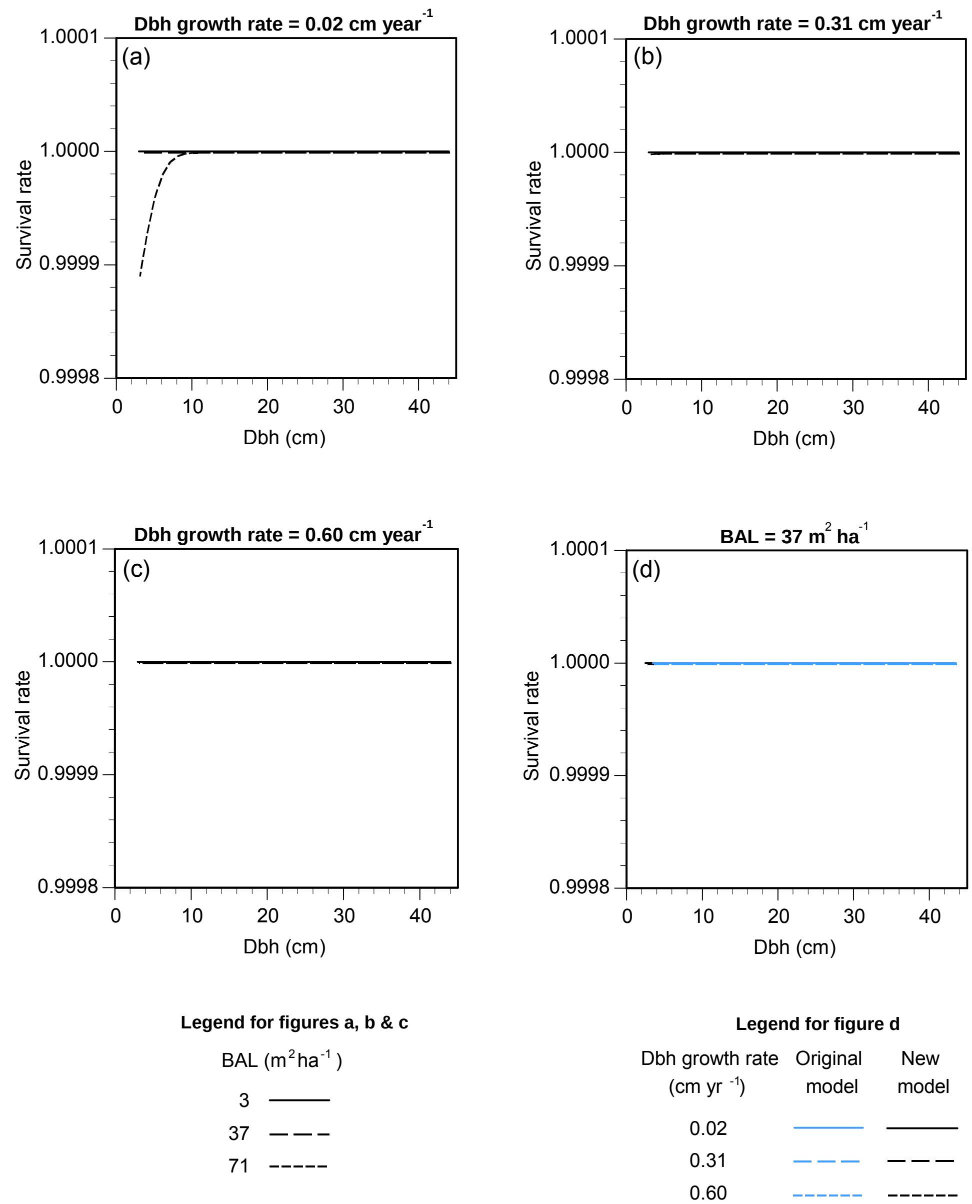
Appendix 4.6: Predicted survival rate for white birch in natural stands as a function of dbh for different conditions of dbh growth rate using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



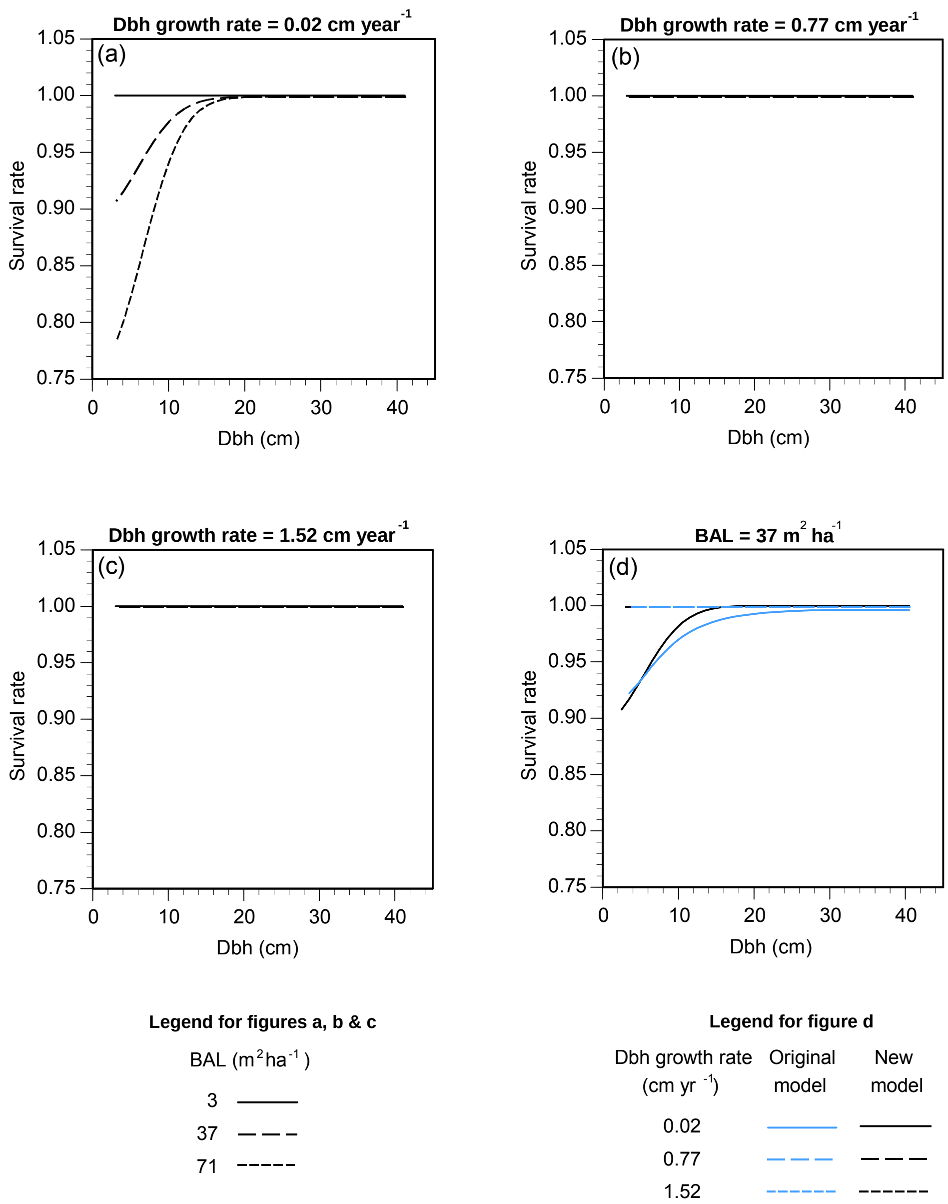
Appendix 4.7: Predicted survival rate for sugar maple in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



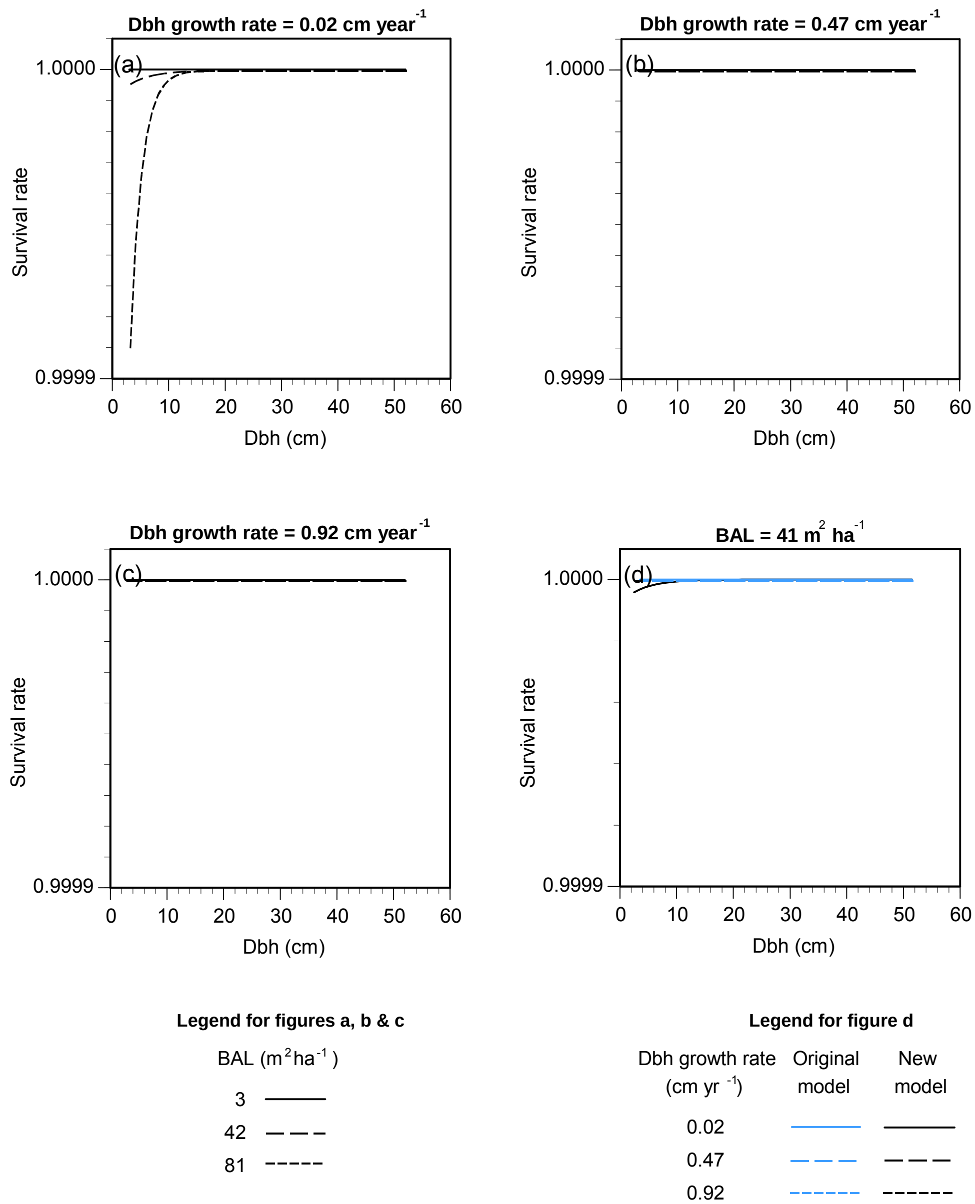
Appendix 4.8: Predicted survival rate for white pine in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



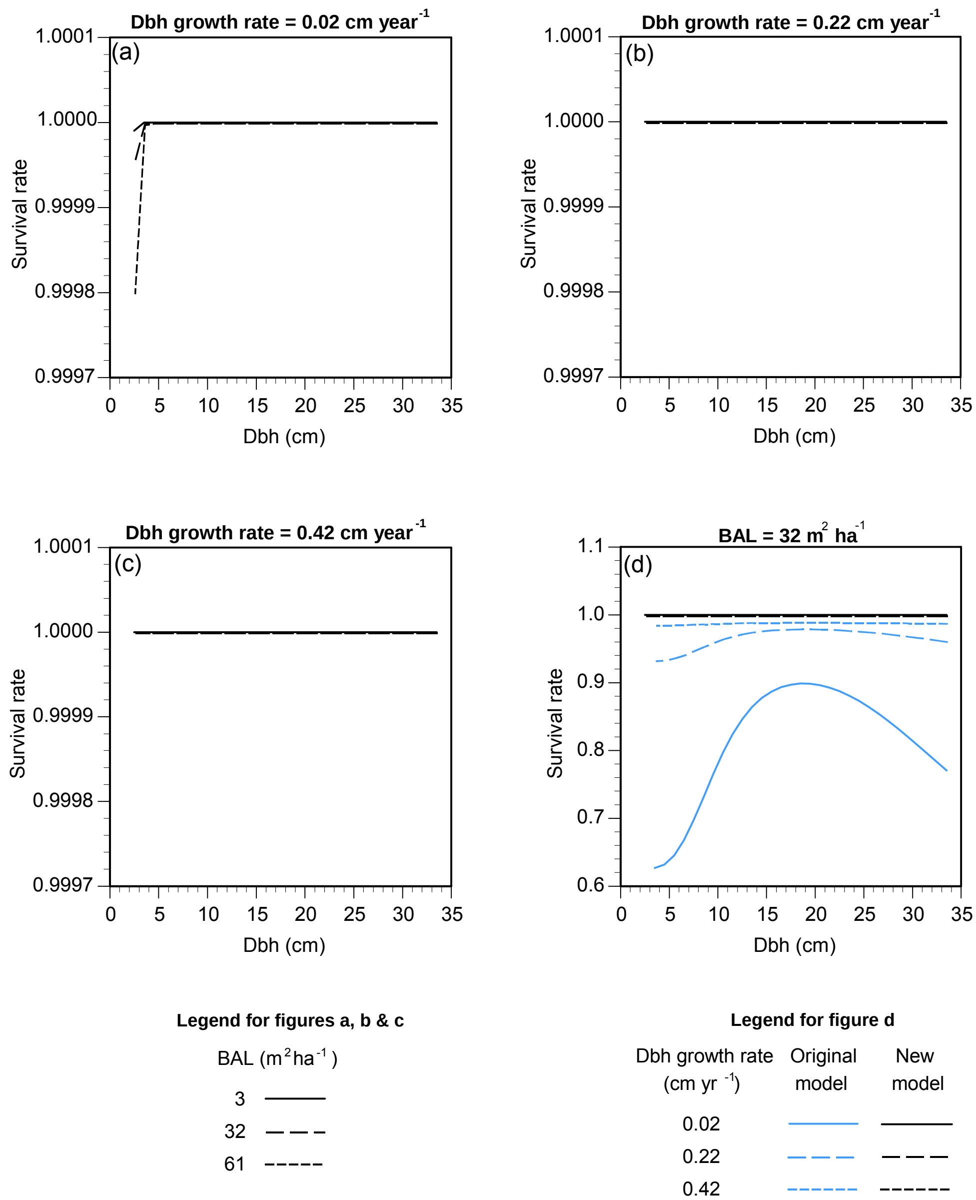
Appendix 4.9: Predicted survival rate for red pine in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



Appendix 4.10: Predicted survival rate for planted red pine as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).

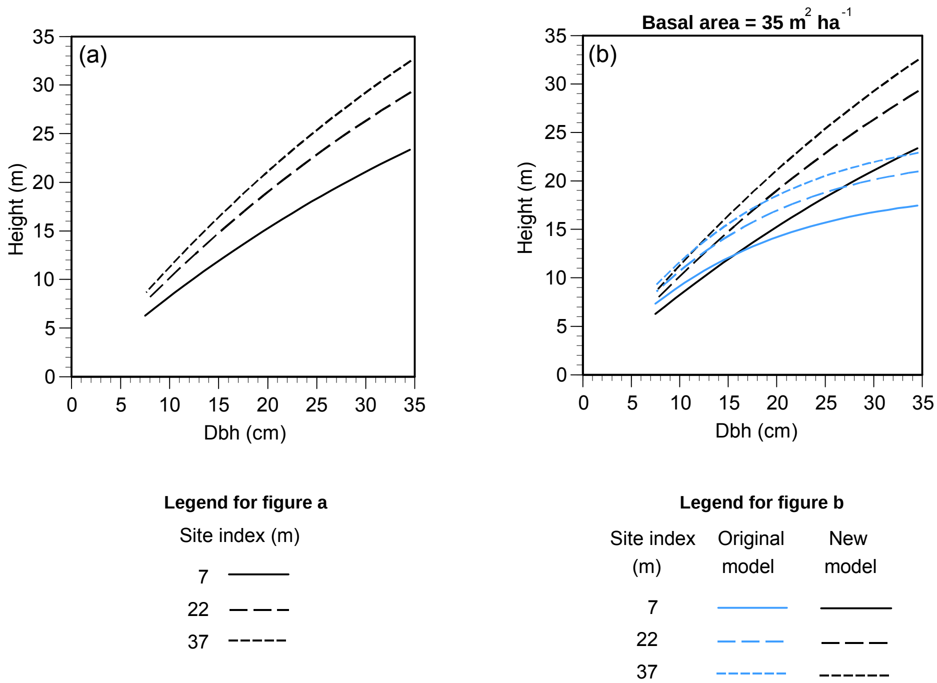


Appendix 4.11: Predicted survival rate for American beech in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).

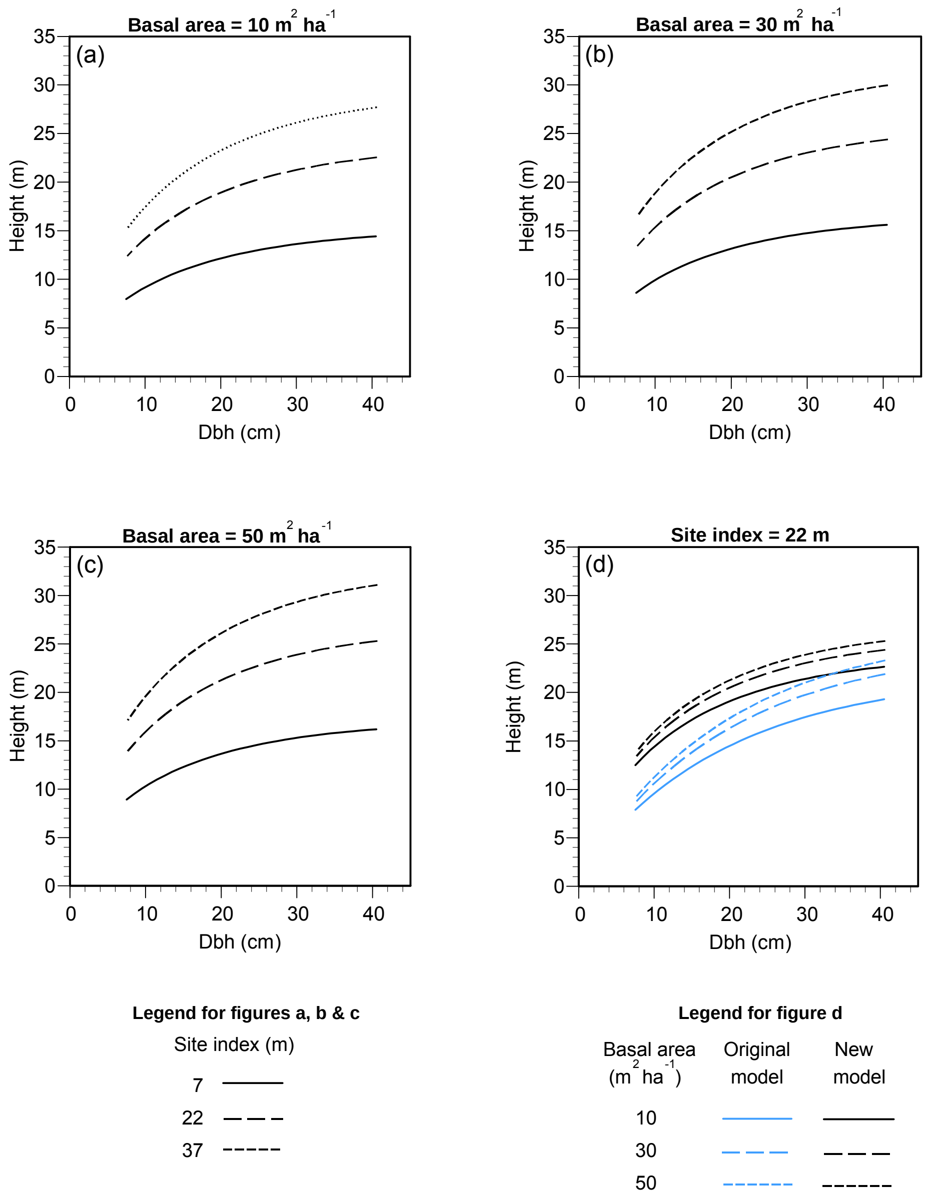


Appendix 4.12: Predicted survival rate for balsam poplar in natural stands as a function of dbh for different conditions of BAL and dbh growth rate using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).

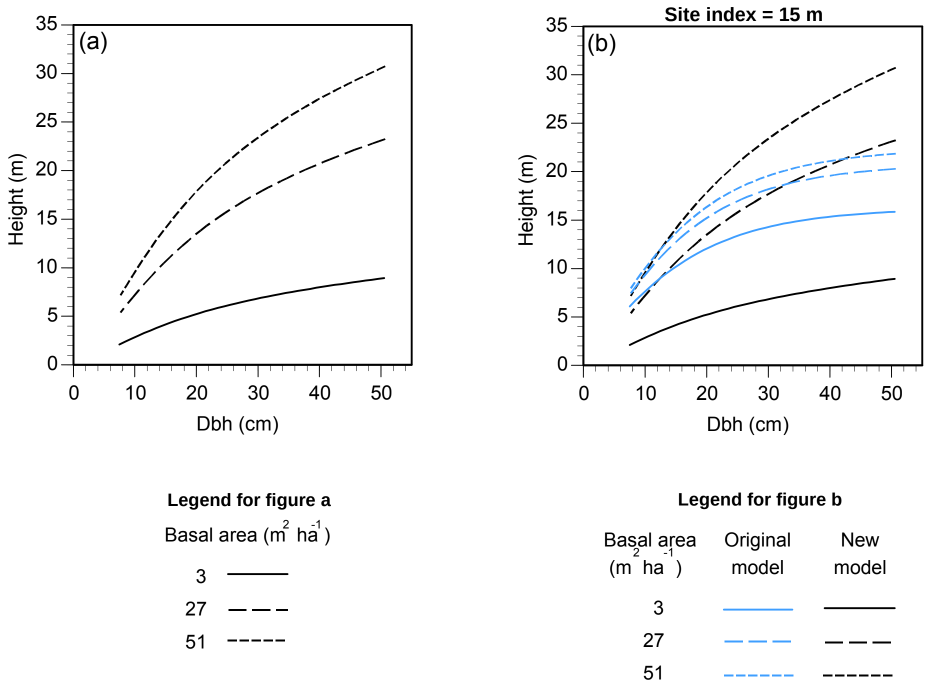
Appendix 5. Biological consistency analysis for height-dbh models



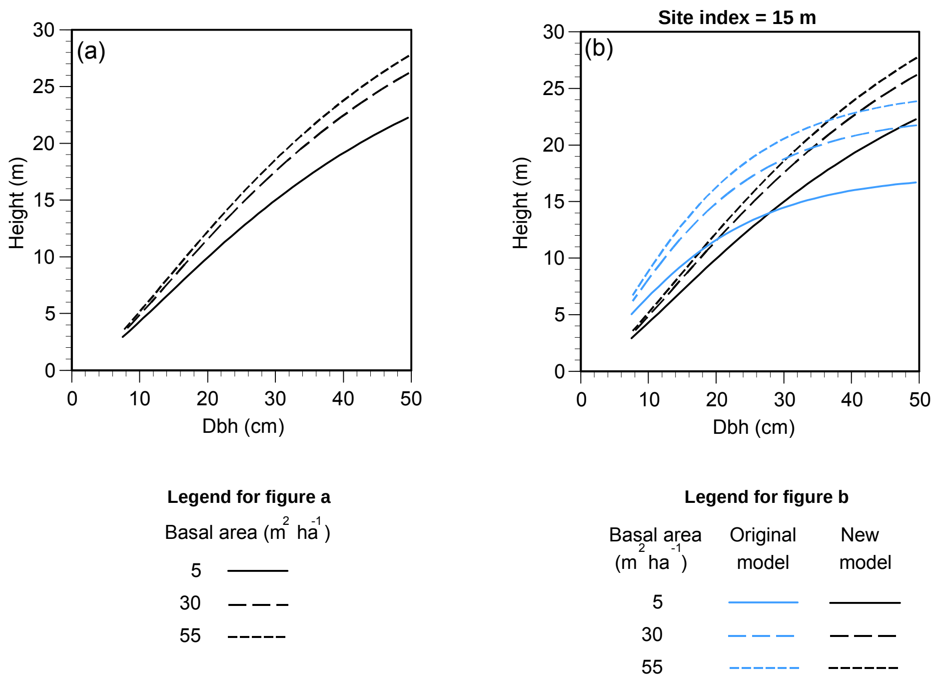
Appendix 5.1: Predicted height for black spruce in natural stands as a function of dbh for different conditions of site index using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



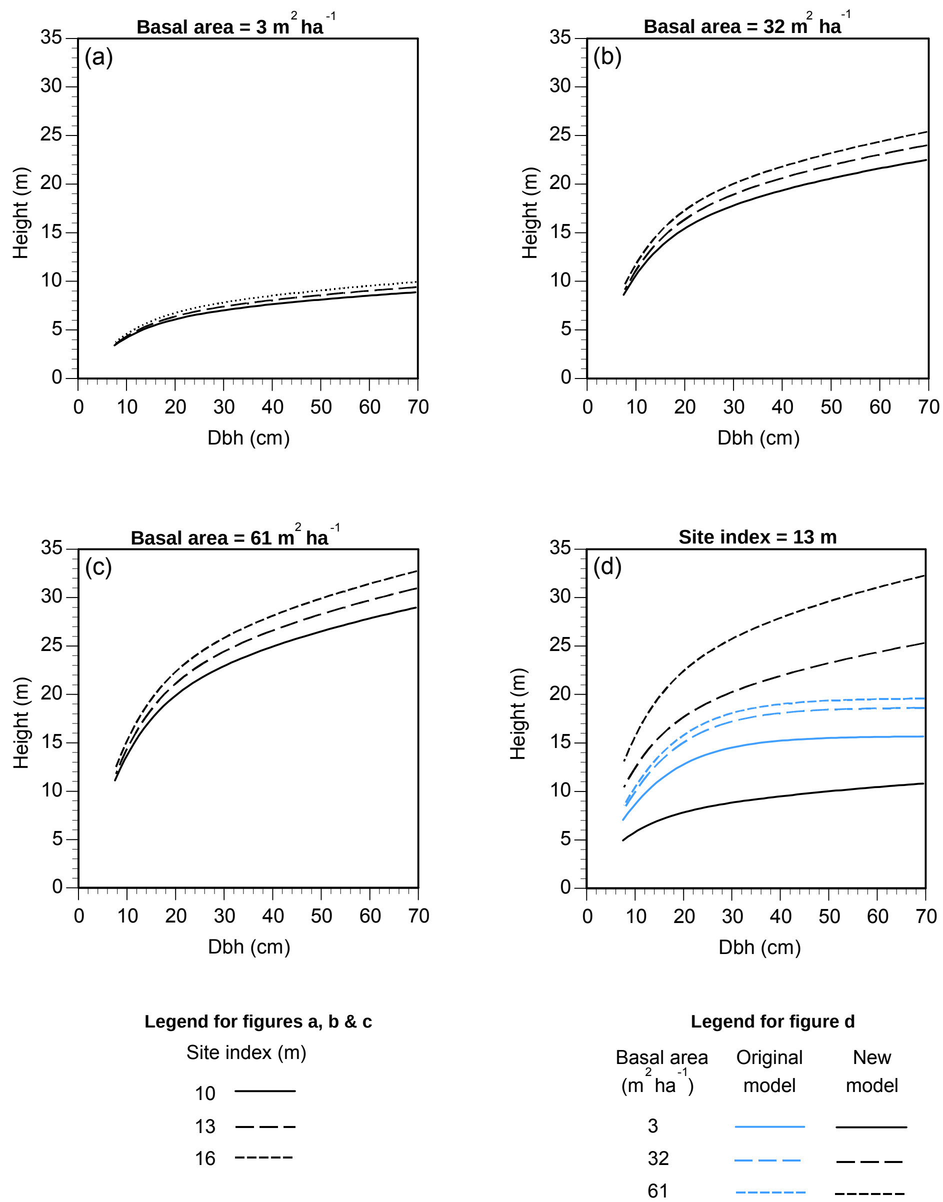
Appendix 5.2: Predicted height for jack pine in natural stands as a function of dbh for different conditions of site index and basal area using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



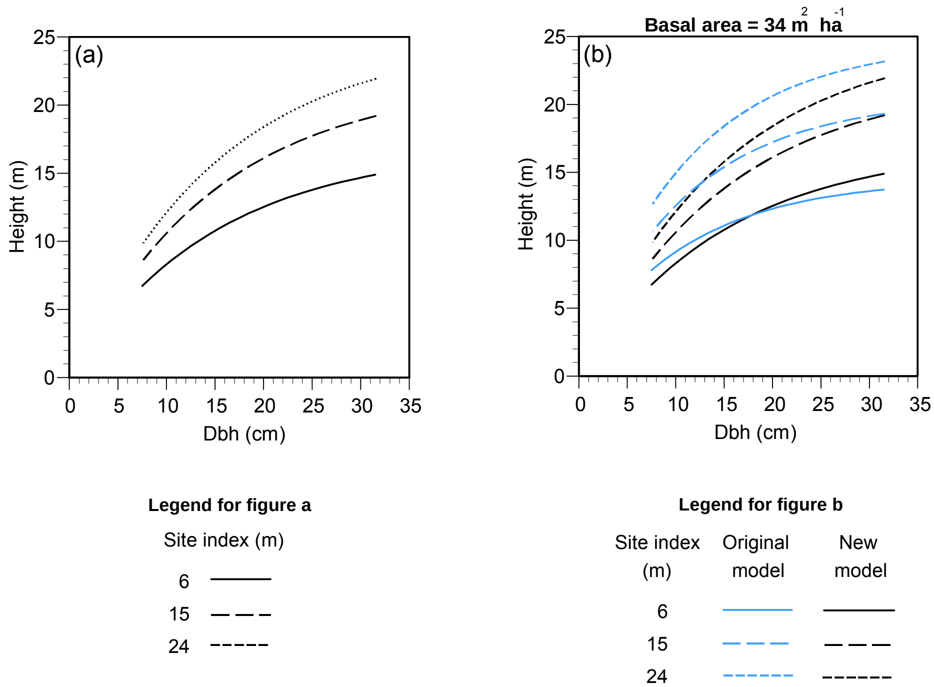
Appendix 5.3: Predicted height for balsam fir in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



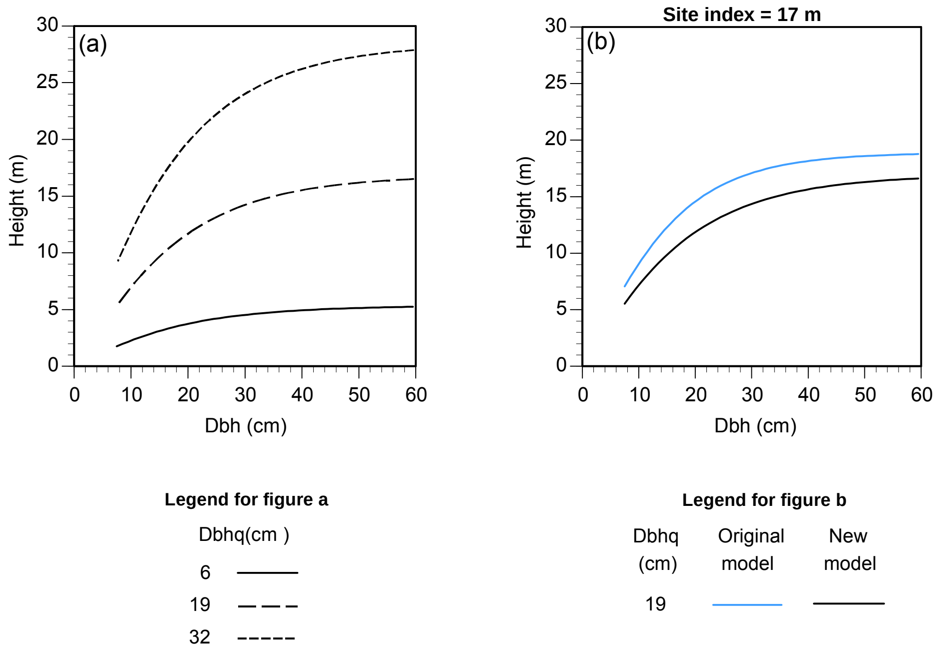
Appendix 5.4: Predicted height for planted white spruce as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



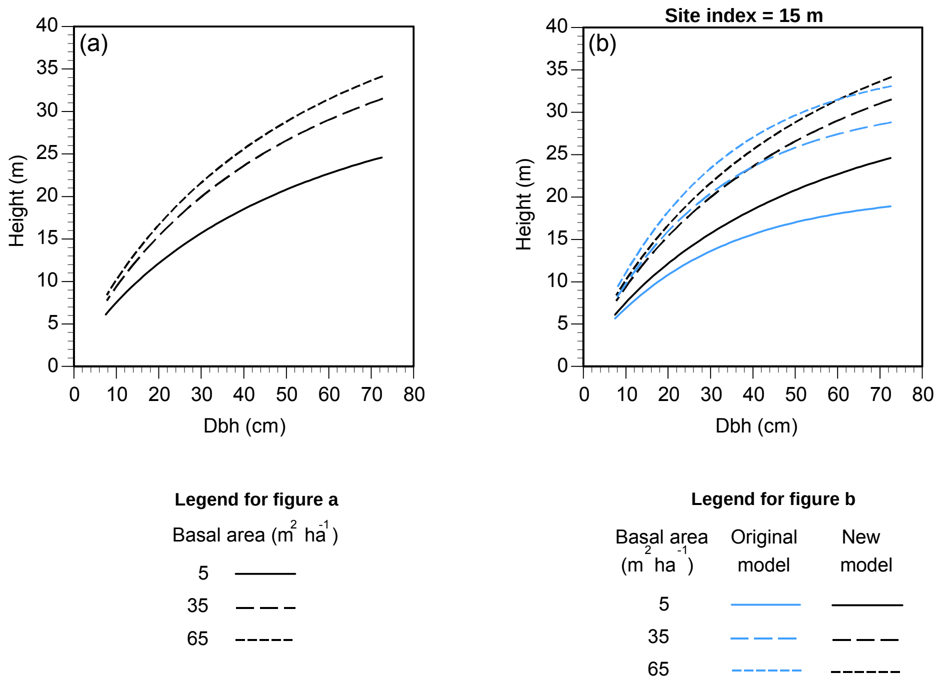
Appendix 5.5: Predicted height for trembling aspen in natural stands as a function of dbh for different conditions of site index and basal area using the new model derived for FVS (Figures a, b & c) and comparison of the original and new FVS models (Figure d).



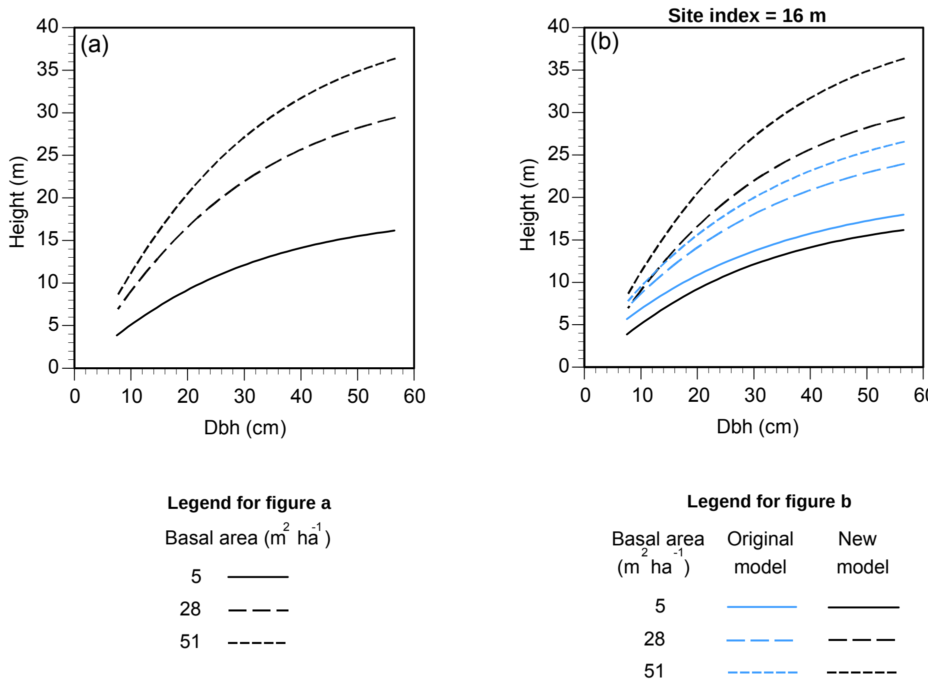
Appendix 5.6: Predicted height for white birch in natural stands as a function of dbh for different conditions of site index using the new model derived for FVS (Figures a) and comparison of the original and new FVS models (Figure b).



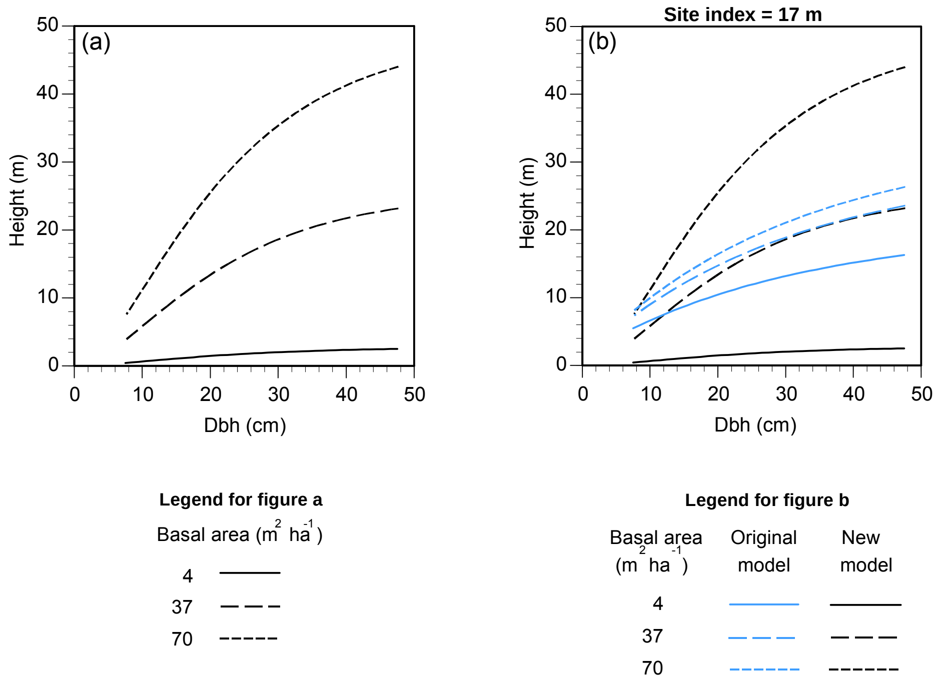
Appendix 5.7: Predicted height for sugar maple in natural stands as a function of dbh for different conditions of quadratic mean diameter (qdbh) using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



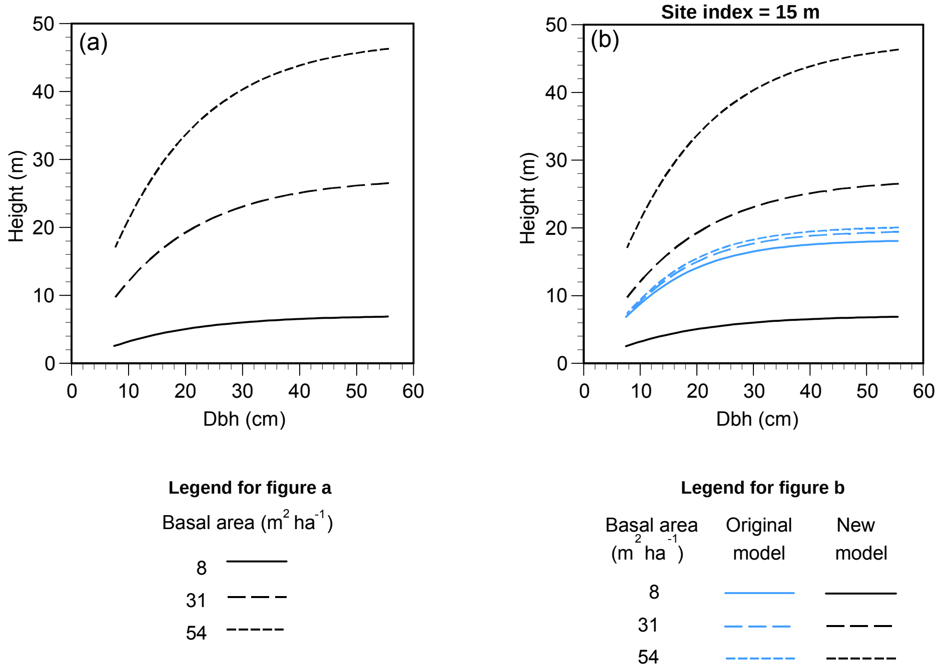
Appendix 5.8: Predicted height for white pine in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



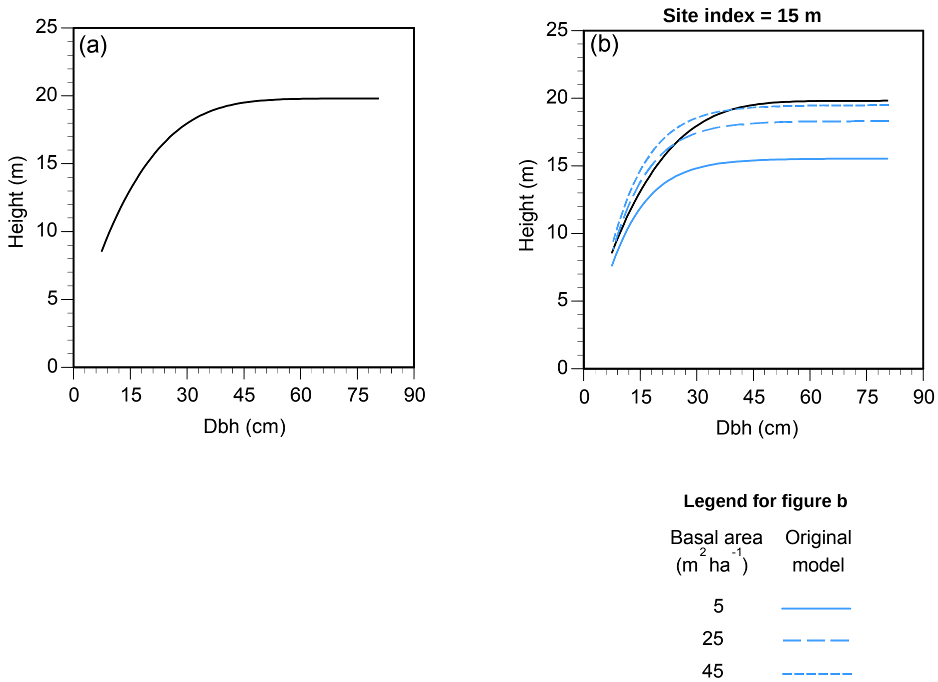
Appendix 5.9: Predicted height for red pine in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



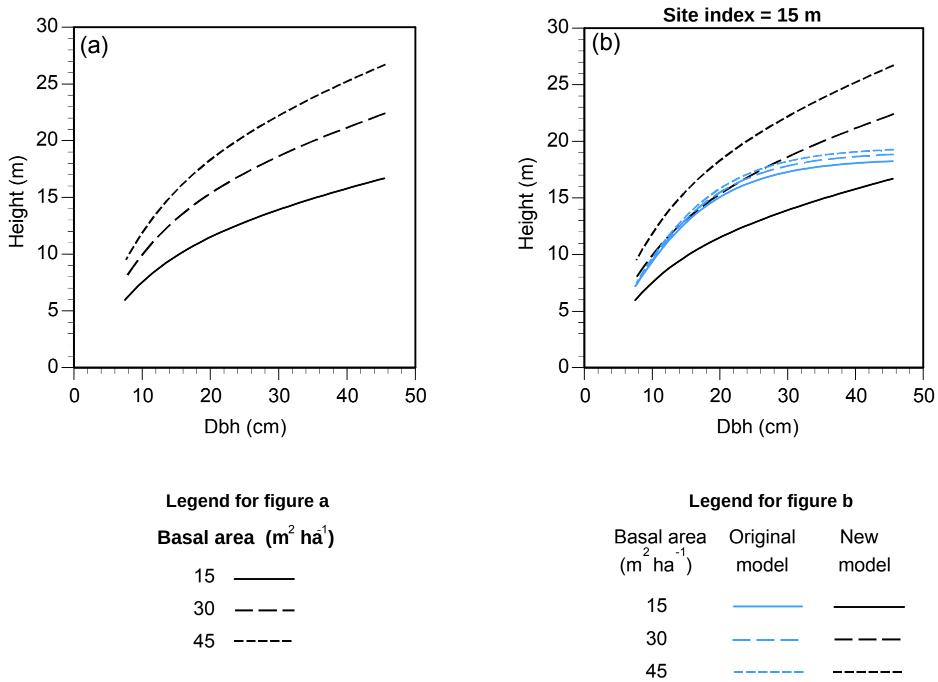
Appendix 5.10: Predicted height for planted red pine as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



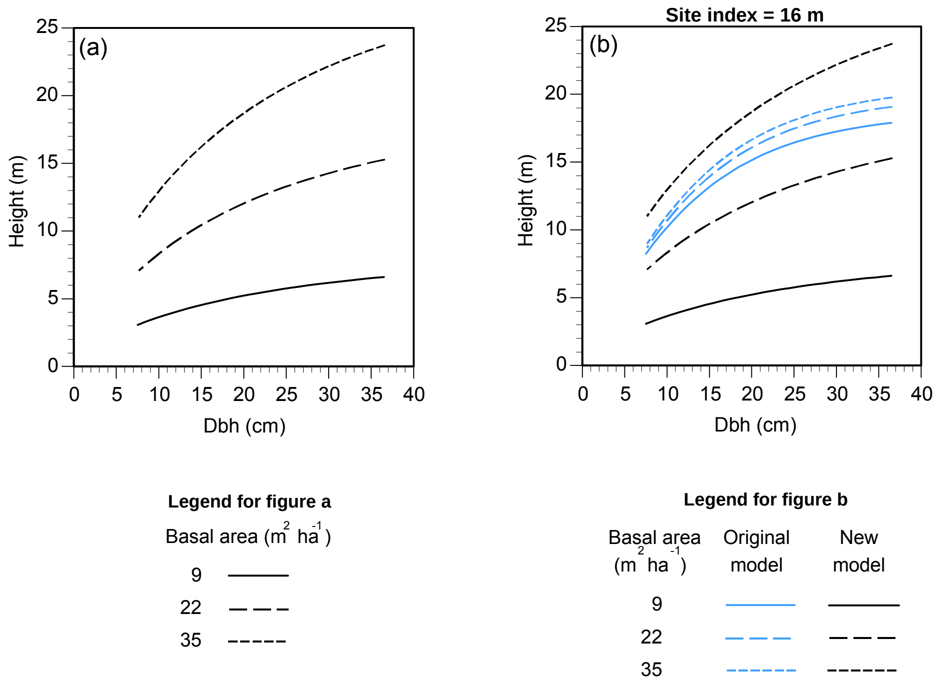
Appendix 5.11: Predicted height for American beech in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



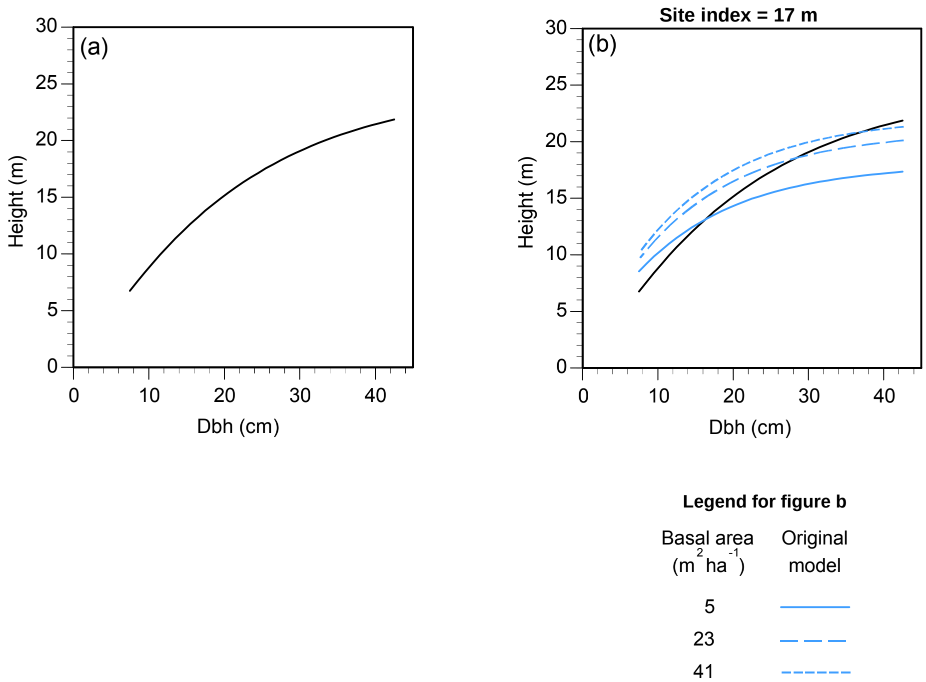
Appendix 5.12: Predicted height for yellow birch in natural stands as a function of dbh using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).



Appendix 5.13: Predicted height for basswood in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).

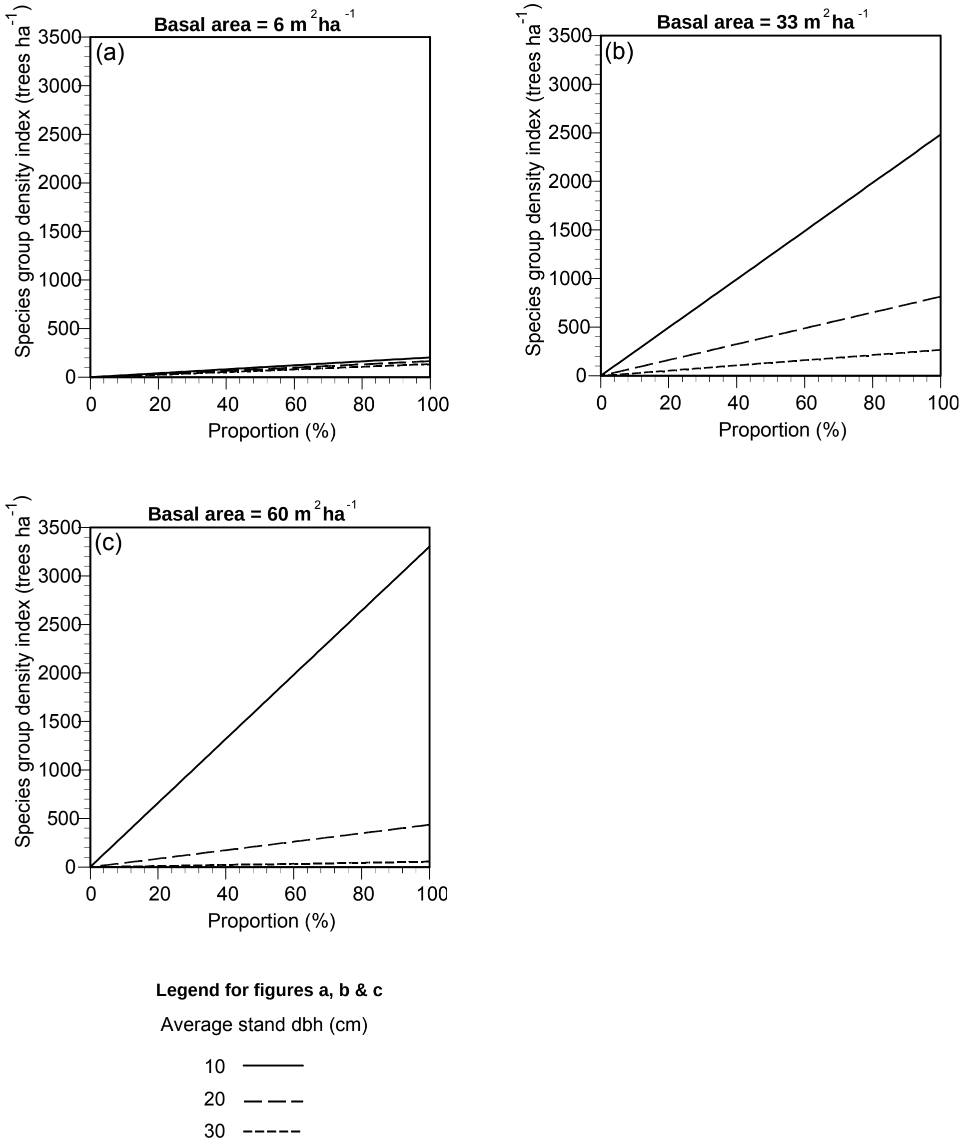


Appendix 5.14: Predicted height for ironwood, silver maple and white ash in natural stands as a function of dbh for different conditions of basal area using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).

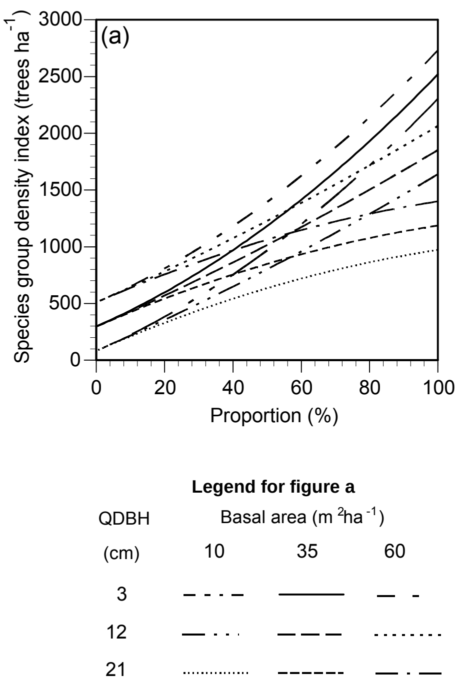


Appendix 5.15: Predicted height for red oak in natural stands as a function of dbh using the new model derived for FVS (Figure a) and comparison of the original and new FVS models (Figure b).

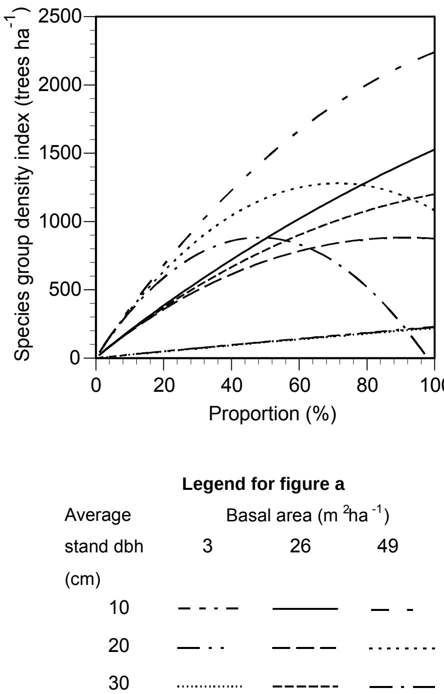
Appendix 6. Biological consistency analysis for the species group density index models



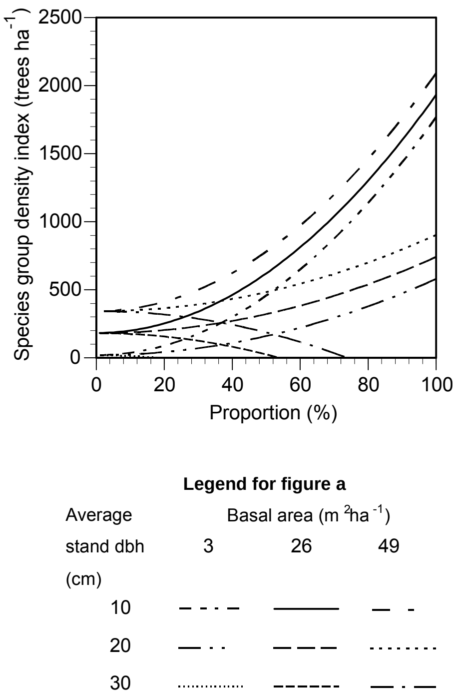
Appendix 6.1: Species group density index predicted for the black spruce species group as a function of the proportion of black spruce in the stand for different conditions of basal area and average stand dbh using the new model derived for FVS (Figures a, b & c).



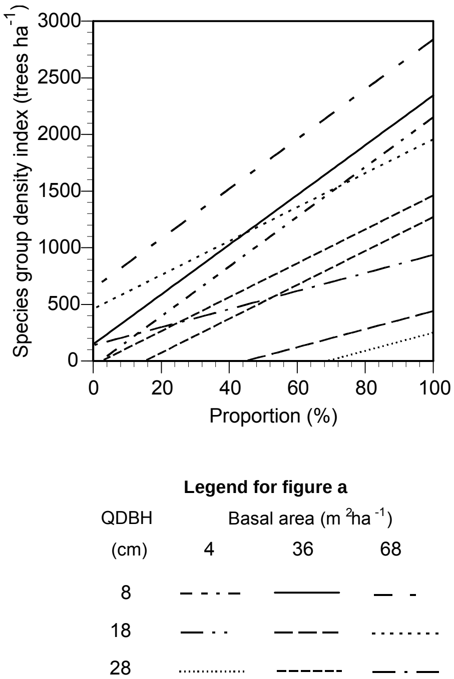
Appendix 6.2: Species group density index predicted for the jack pine species group as a function of the proportion of jack pine in the stand for different conditions of quadratic mean diameter (qdbh) and basal area using the new model derived for FVS (Figure a).



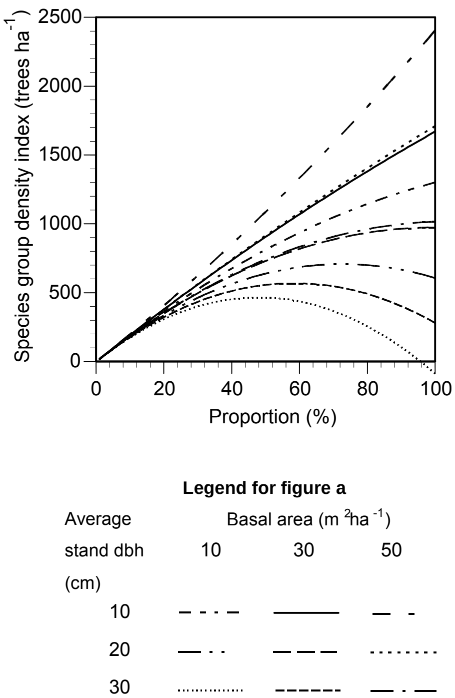
Appendix 6.3: Species group density index predicted for the white spruce species group as a function of the proportion of planted white spruce for different conditions of basal area and average stand dbh using the new model derived for FVS (Figure a).



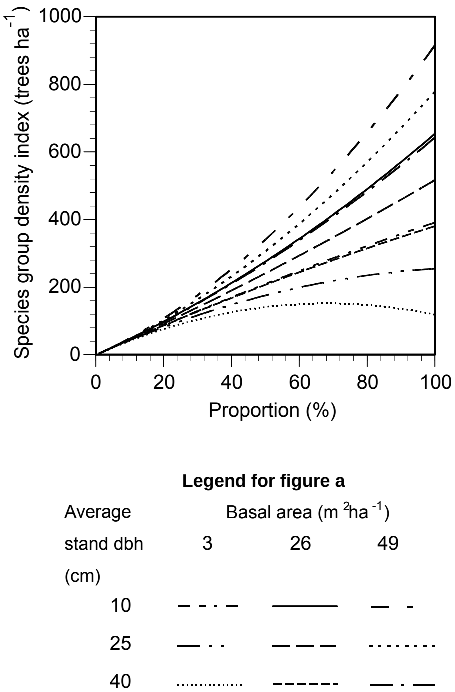
Appendix 6.4: Species group density index predicted for the trembling aspen species group as a function of the proportion of trembling aspen in the stand for different conditions of basal area and average stand dbh using the new model derived for FVS (Figure a).



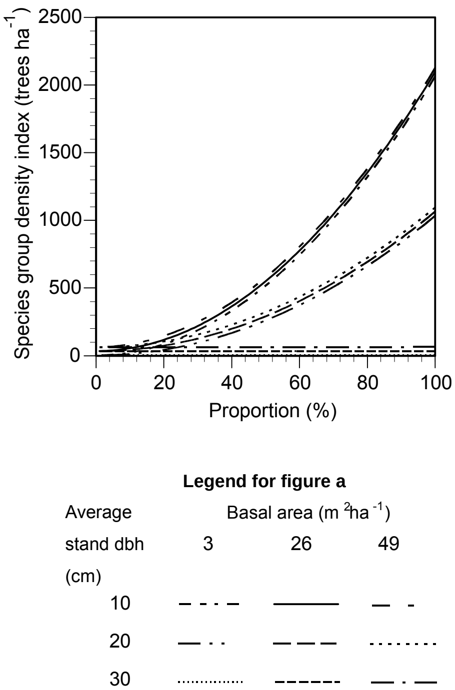
Appendix 6.5: Species group density index predicted for the white birch species group as a function of the proportion of white birch in the stand for different conditions of quadratic mean diameter (qdbh) and basal area using the new model derived for FVS (Figure a).



Appendix 6.6: Species group density index predicted for the red and white pine species group as a function of the proportion of red and white pines in the stand for different conditions of basal area and average stand dbh using the new model derived for FVS (Figure a).

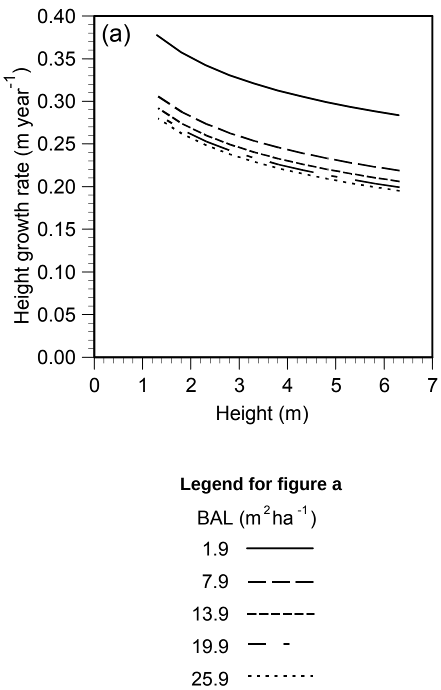


Appendix 6.7: Species group density index predicted for the northern hardwood species group as a function of the proportion of northern hardwood species for different conditions of basal area and average stand dbh using the new model derived for FVS (Figure a).

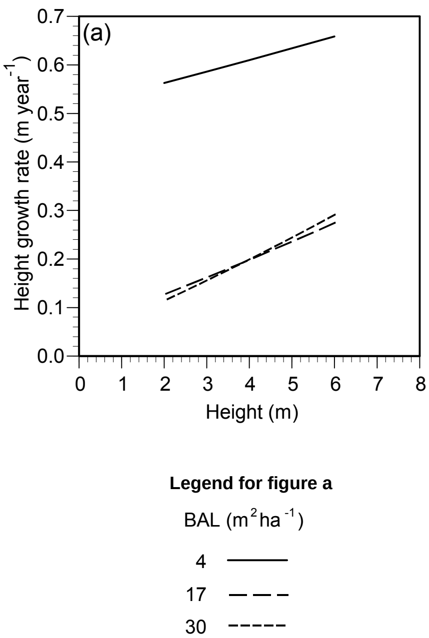


Appendix 6.8: Species group density index predicted for the red oak species group as a function of the proportion of red oak for different conditions of basal area and average stand dbh using the new model derived for FVS (Figure a).

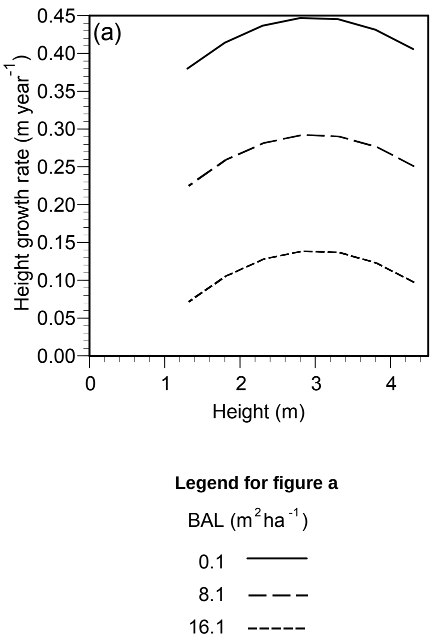
Appendix 7. Biological consistency analysis for small-tree height growth rate models



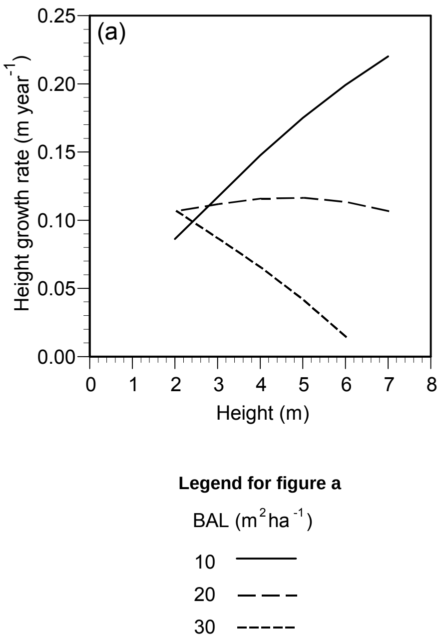
Appendix 7.1: Predicted small-tree height growth rate for black spruce in natural stands as a function of height for different conditions of BAL using the new model derived for FVS (Figure a).



Appendix 7.2: Predicted small-tree height growth rate for balsam fir in natural stands as a function of height for different conditions of BAL using the new model derived for FVS (Figure a).

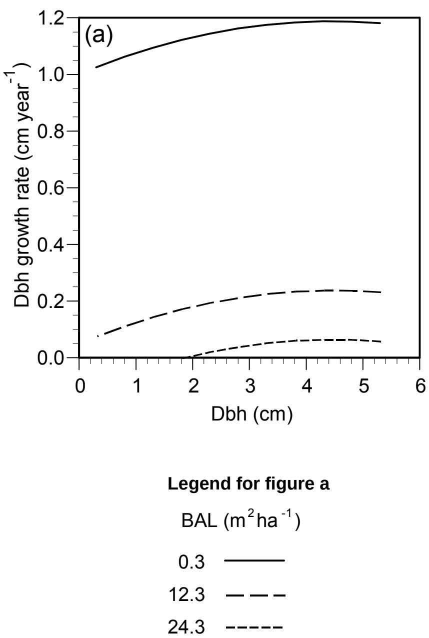


Appendix 7.3: Predicted small-tree height growth rate for planted white spruce as a function of height for different conditions of BAL using the new model derived for FVS (Figure a).

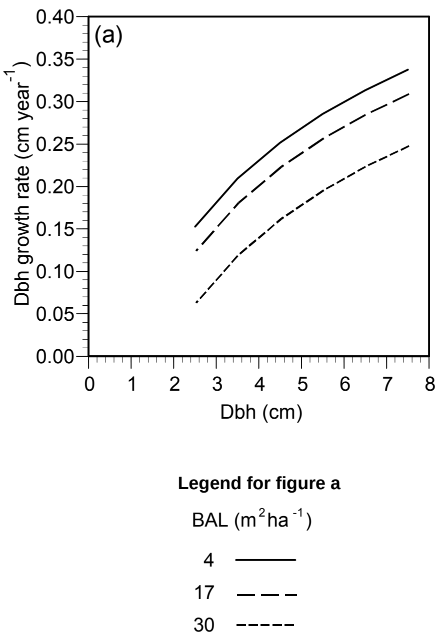


Appendix 7.4: Predicted small-tree height growth rate for white pine in natural stands as a function of height for different conditions of BAL using the new model derived for FVS (Figure a).

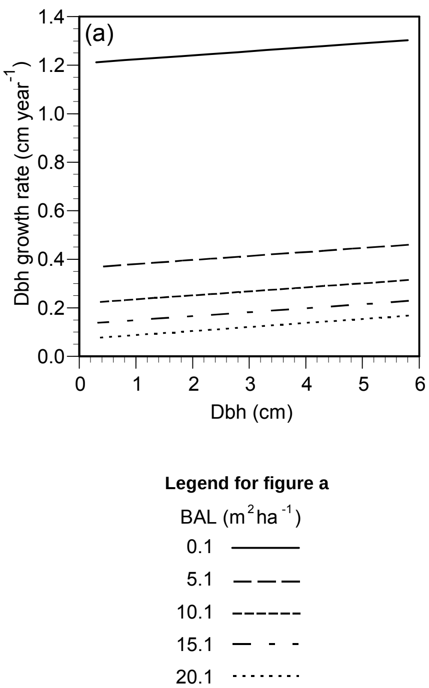
Appendix 8. Biological consistency analysis for small-tree dbh growth rate models



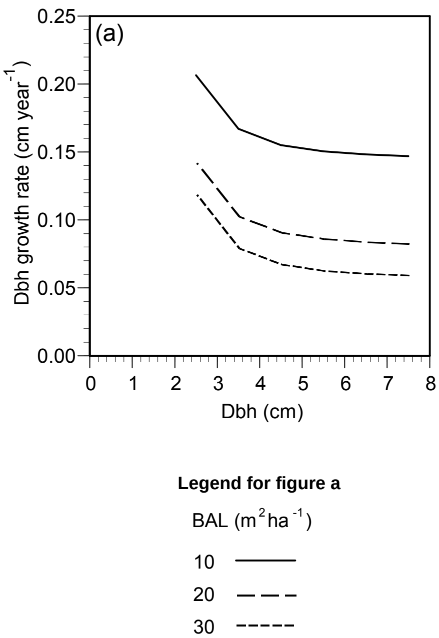
Appendix 8.1: Predicted small-tree dbh growth rate for black spruce in natural stands as a function of dbh for different conditions of BAL using the new model derived for FVS (Figure a).



Appendix 8.2: Predicted small-tree dbh growth rate for balsam fir in natural stands as a function of dbh for different conditions of BAL using the new model derived for FVS (Figure a).



Appendix 8.3: Predicted small-tree dbh growth rate for planted white spruce as a function of dbh for different conditions of BAL using the new model derived for FVS (Figure a).



Appendix 8.4: Predicted small-tree dbh growth rate for white pine in natural stands as a function of dbh for different conditions of BAL using the new model derived for FVS (Figure a).