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Contents

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Nova Scotia Hardwood Growth and Yield Model

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Executive Summary

The 2005 update of the hardwood growth and yield model used a database that had increased in size by approximately 50% since the original 1997 model was developed. Natural unmanaged growth functions for average height, total diameter and total density were each updated to incorporate new data and quantify growth differences among different species and sites. The managed stand growth functions were updated to capture differences in diameter growth for different species. Lastly, the merchantable and sawlog conversion functions in the model were updated to account for treatment status and incorporate new sawlog specifications. In the 1997 model sawlog specifications were 15.24cm (6in) DBH and 10.16cm (4in) top while the 2005 update used a 25.4cm (10in) DBH and 20.32cm (8in) top.

The evaluation of the new model initially compared the 2005 natural unmanaged growth predictions to observations in the Inventory PSP database. The comparison highlighted the natural unmanaged growth functions were generating predictions within expected ranges. In addition, all observations supported one of the fundamental assumptions of the model being that, it represents growth and development in normal (fully stocked) stands. A second component of the evaluation compared age based predictions to observations from the Research PSP database. Compilation of the residual statistics showed the model was relatively accurate for all stand characteristics, species groups and product classes. One exception was the sawlog product class where estimates for the intolerant and Aspen species groups were less accurate. Comparing the compiled residual statistics to those compiled for the 1997 model showed the updated model performed on par and in most cases better than the 1997 model, for all predicted stand characteristics by species group and product class.

The evaluation results show the 2005 update to be a significant improvement to the Nova Scotia hardwood growth and yield model. The adoption of the model will improve the accuracy of forecasts for hardwood development in natural and managed stands.

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1 Introduction

In Nova Scotia, hardwood forest types represent a large proportion of the forest resource. Inventoried hardwood stands account for approximately 12% for the forested area and 14% of the merchantable volume (NSDNR, 2004b). Since 1960 the hardwood harvest has grown substantially (Figure 1) reflecting a greater demand on the provincial hardwood resource. Understanding the growth and development of hardwoods is important to ensuring appropriate management and utilization of our resource.

Growth and yield models are an important tool to sustainable resource planning. There are a wide range of approaches and techniques currently in use. The approach chosen is generally a function of the available data and intended use of the product.

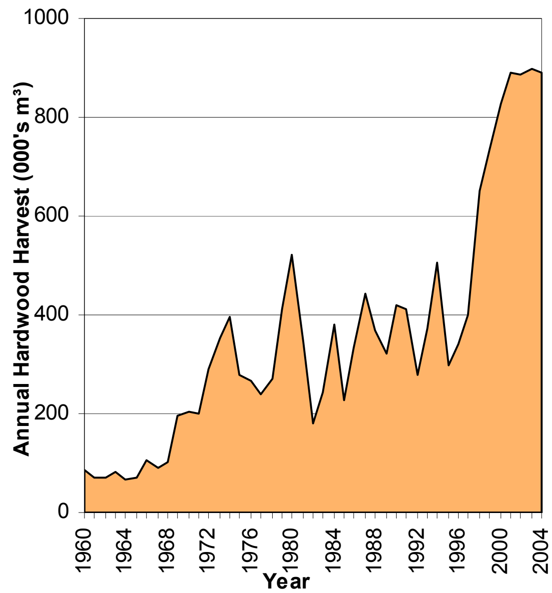


Figure 1. Nova Scotia hardwood harvest levels since 1960.

In Nova Scotia, the beginnings of stand level growth and yield modeling can be traced back to the 1960's with the establishment of the permanent sample plot (PSP) program. From there, work on a stand level growth and yield model continued which culminated with the completion of a set of site index based softwood normal yield tables (RNYT) for the province (NSDNR, 1990). Later, the RNYT project was expanded to model the impact of management activities (planting, precommercial thinning, commercial thinning) at the stand level. This eventually led to the development of the softwood growth and yield model (NSDNR, 1993).

In addition to the softwood model there were also efforts directed towards the development of a hardwood growth and yield model. In 1987, hardwood site index curves were finished (NSDNR, 1987) and later, the softwood growth and yield modeling approach was adapted for hardwood stands (NSDNR, 1997). This initial hardwood growth and yield model was later merged with the softwood model under a common interface (NSDNR, 2001).

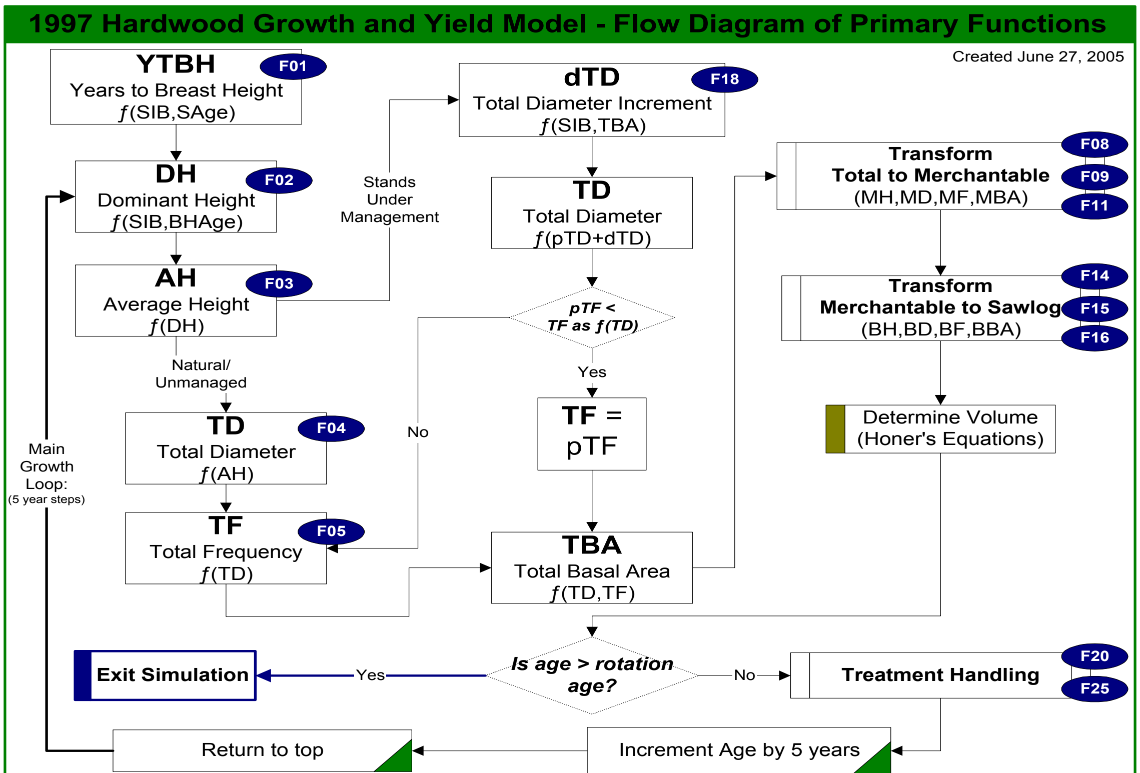
The purpose of this report is to describe updates made to the hardwood growth and yield model. The goal was to refit existing growth functions to a PSP database that has nearly doubled in size since the initial functions were constructed. A second objective was to investigate updating existing functions or developing new functions to better capture species group and site class variation.

2 Overview of Existing Model

The existing hardwood growth and yield model was primarily developed between 1996 and 1997 (NSDNR, 1997). In this report, it is referred to as the 1997 model. The model has several defining characteristics / assumptions:

1) Even-Aged Stands 2) Fully Stocked[1]
3) Single Species (hardwood)[2] 4) Site Specific
5) Treatment Specific (PCT and CT)

Figure 2 and Table 1 provide an overview of the 1997 model and its functions. Appendix I contains a more detailed flow diagram.



Legend — FXX Refers to a function developed from PSP data; Functions can be found in Table 1.

Code	Units	Description	Code	Units	Description
SAge	years	Stump Age	MH	m	Merchantable (dbh >=9.1cm) Avg. Height
BHAge	years	Breast Height Age	MD	cm	Merchantable Diameter at Breast Height
SIB	m	Site Index @ 50yrs (Breast Height Age)	MF	stems/ha	Merchantable Frequency
YTBH	years	Years to Breast Height	MBA	m²	Merchantable Basal Area
DH	m	Dominant Height	BH	m	Sawlog (dbh >=18cm) Avg. Height
AH	m	Average Total Height	BD	cm	Sawlog Diameter at Breast Height
TD	cm	Total Diameter at Breast Height	BF	stems/ha	Sawlog Frequency
TF	stems/ha	Total Frequency	BBA	m²	Sawlog Basal Area
TBA	m²	Total Basal Area	pTD	cm	Total Diameter in Previous Period
dTD	cm	Total Diameter Increment (5yr) (Treated)	pTF	stems/ha	Total Frequency in Previous Period

Figure 2. 1997 hardwood growth and yield model flow diagram highlighting primary functions.

[1] Different stocking levels can be approximated by discounting outputs using the ratio of existing stand basal area to the normal fully stocked basal area.
[2] Some species level consideration was introduced by using Honer's species coefficients (Honer, 1967).

Table 1. Functions used in the 1997 hardwood growth and yield model.

Function		Coefficients					
Code	**Description/Model**	**ß0**	**ß1**	**ß2**	**ß3**	**N**	**r^2**
F01[1]	**YTBH as ƒ(SIB)** where: SIB = Site Index(m); YTBH = Years to Breast Height(yrs)						
	$YTBH = ß0 - ß1*SIB+ß2*SIB^{ß3}$	10.5513	0.7565	0.0339	1.7826	N/A	N/A
F02[1]	**DH as ƒ(SIB,BHAge)** where: SIB = Site Index(m); BHAge = Breast Height Age(yrs); DH = Dominant Height(m)						
	DH = See NSDNR 1987 Report[1]	N/A	N/A	N/A	N/A	N/A	N/A
F03	**AH as ƒ(DH)** where: DH = Dominant Height(m); AH = Total Lorey's Height(m)						
	$AH = ß0+ß1*DH$	-0.4657	0.9451	N/A	N/A	282	0.973
F04	**TD as ƒ(AH)** where: AH = Total Lorey's Height(m); TD = Total Quadratic Mean Diameter(cm)						
	$TD = ß0*AH^{ß1}$	0.3572	1.3381	N/A	N/A	282	0.769
F05	**TF as ƒ(TD)** where: TD = Total Quadratic Mean Diameter(cm); TF = Total Stem Frequency(stems/ha)						
	$TF = 10^{(ß0+ß1*Log10(TD))}$	5.1266	-1.611	N/A	N/A	282	0.879
F08	**MHrat as ƒ(TD)** where: TD = Total Quadratic Mean Diameter(cm); MHrat = [Merchantable Lorey's Height/Total Lorey's Height]						
	$MHrat = (1+e^{ß0*TD})^{ß1}$	-0.1971	0.4896	N/A	N/A	271	0.784
F09	**MD as ƒ(TD)** where: TD = Total Quadratic Mean Diameter(cm); MD = Merchantable Quadratic Mean Diameter(cm)						
	$MD = ß0+ß1*TD$	5.9041	0.7629	N/A	N/A	271	0.827
F11	**MBArat as ƒ(TD)** where: TD = Total Quadratic Mean Diameter(cm); MBArat = [Merchantable Basal Area/Total Basal Area]						
	$MBArat = (1-e^{ß0*TD})^{ß1}$	-0.3746	10.856	N/A	N/A	271	0.899
F14	**BHrat as ƒ(MD)** where: MD = Merchantable Quadratic Mean Diameter(cm); BHrat = [Board Lorey's Height/Merchantable Lorey's Height]						
	$BHrat = (1+e^{ß0*MD})^{ß1}$	-0.1434	0.3774	N/A	N/A	232	0.253
F15	**BD as ƒ(MD)** where: MD = Merchantable Quadratic Mean Diameter(cm); BD = Board Quadratic Mean Diameter(cm)						
	$BD = ß0+ß1*MD$	5.2143	0.8323	N/A	N/A	232	0.958
F16	**BBArat as ƒ(MD)** where: MD = Merchantable Quadratic Mean Diameter(cm); BBArat = [Board Basal Area/Merchantable Basal Area]						
	$BBArat = (1-e^{ß0*MD})^{ß1}$	-0.3995	143.75	N/A	N/A	232	0.868
F18	**ΔTD as ƒ(SIB,TBA)** where: SIB = Site Index(m); TBA = Total Basal Area(m^2/ha); ΔTD = 5 Year Increment to Total Quadratic Mean Diameter(cm)						
	$\Delta TD = (ß0+SIB*ß1)*e^{(ß2+SIB*ß3*)*TBA}$	-.7179	0.1835	-.0062	-.0014	636	0.346
F20	**AI-TD-CT as ƒ(TD,BArem)** where: TD = Total Quadratic Mean Diameter(cm); BArem = Percent of Total Basal Area Removed in Treatment(%); AI-TD-CT = Artificial Increase in Total Quadratic Mean Diameter after Commercial Thinning(cm)						
	$AI\text{-}TD\text{-}CT = ß0+ß1*TD+ß2*BArem$	2.2040	1.0660	0.0180	N/A	187	0.481
F25	**AI-TD-PCT as ƒ(TD,SP)** where: TD = Total Quadratic Mean Diameter(cm); SP = Spacing following Treatment(m); AI-TD-PCT = Artificial Increase in Total Quadratic Mean Diameter after Precommercial Thinning(cm)						
	$AI\text{-}TD\text{-}PCT = ß0+ß1*TD+ß2*SP$	0.1669	0.7876	0.2011	N/A	N/A	N/A

Note: 1) For details on the DH or YTBH functions see: NSDNR. 1987. *Site Index Curves for hardwoods in Nova Scotia. Forest Research Report 1. 7pp.*

3 Data Description

The update of the hardwood growth and yield model used two Permanent Sample Plot (PSP) datasets: the Research PSPs and the Inventory PSPs.

The Research PSP database represents a sample selectively placed in stands considered to be fully stocked. The location of plots focused on stands where control plots could be established alongside treated plots. For more information on the Research PSP database see the following procedures manual (NSDNR, 1998). This analysis used all data up to and including the 2003 measurement. In all, 368 hardwood PSPs were used that had a total of 1,746 measurements. Functions for the 1997 model were based solely on the Research PSP database.

The Inventory PSP database represents an unbiased sample randomly placed throughout the forests of the province. For more details on the Inventory PSPs see the specifications manual (NSDNR, 2004a). All measurements up to and including 2003 were used for analysis. The database contained 814 hardwood PSPs with 2,351 measurements. The Inventory PSP database was used as a validation database. Initially it was thought the data could augment species groups with poor representation in the Research PSP database, however, the database was not compatible and therefore not used for any model development. The main reasons why the Inventory PSP database was in compatible with the Research PSP database were:

1. Relative to the Research PSPs the Inventory PSPs had high levels of tree-level variation within plots as related to height, diameter, frequency and species.
2. Within the Inventory PSP database individual tree measurements were limited to merchantable (DBH >9.1cm) stems, unlike the Research PSPs that measured all trees greater than 4cm DBH (Diameter at Breast Height).

Table 2 further summarizes differences between the two datasets.

Table 2. Summary of differences between the Research PSP and Inventory PSP databases.

Database Attribute	Research PSP	Inventory PSP
Sample Design	Selective	Random
Plot Size	Variable (Minimum of 30 trees)	0.04ha Fixed Area
Total PSPs (Measurements)	1,185 (4,579)	3,349 (14,666)
Hardwood PSPs (Measurements)	368 (1,746)	814 (2,351)
Minimum Tree Size	4cm DBH	9.1cm DBH[1]
Height Measurements	Sample of 15 Heights	All Heights Measured
Plot Condition (species, basal area, age, DBH)	Generally Uniform	Highly Variable

Note: 1) Trees less than 9.1cm DBH were tallied by species, DBH class and height then placed into a 'Sapling' database.

3.1 Data Compilation

Plot measurements from the Research and Inventory PSP databases were compiled to summarize stand conditions in terms of height, diameter (DBH), density, basal area and volume (Table 3). Compilations were further stratified by three size classes; total, merchantable and sawlog (Table 4). The compilations were performed using the NSDNR Forest Research Information System (FRIS) PSP compilation routine (NSDNR, 2000). The FRIS compilation routine was designed for Research PSPs, therefore the Inventory PSP database needed to be reformatted prior to compilation.

Table 3. Stand level characteristics compiled for PSP databases.

Characteristic	Units	Description
Dominant Height	m	Average height of five tallest trees in the plot.
Average Height	m	Lorey's Height; Average height weighted by basal area.
Quadratic Mean Diameter	cm	DBH of tree of average basal area.
Stem Density	stems/ha	Frequency of trees within plot extrapolated to a per hectare unit
Basal Area	m^2/ha	Sum of basal area of trees in a per hectare unit
Volume	m^3/ha	Sum of tree volumes (derived using Honer's equations (Honer,1967)) in a per hectare unit

Table 4. Tree size classification used for PSP compilations.

Tree Size Class	Minimum DBH Outside Bark		Minimum Top Diameter Inside Bark		Stump Height	
	(cm)	(in)	(cm)	(in)	(m)	(ft)
Total	none	none	none	none	0.15	0.5
Merchantable	9.10	3.6	7.62	3.0	0.15	0.5
Sawlog	25.40	10.0	20.32	8.0	0.15	0.5

Site index was required for each measurement of each PSP. For the Research PSP database, this was derived using the provincial hardwood site index curves (NSDNR, 1987). Heights of the five tallest trees along with an age at breast height were used to compute site index for the plot measurement. A similar process was used for the Inventory PSP database yet the database has specific 'site trees' that are measured for height and age to compute site index.

The plots of the Research PSP database were classified by treatment type. Plots were placed into one of three classes; natural unmanaged, precommercially thinned (PCT) or commercially thinned (CT). The Inventory PSP database did not contain the required treatment history information and, therefore, was not classified by treatment.

Treated plots in the Research PSP database were compiled for change in total quadratic mean diameter (QMD) between measurements (i.e. diameter increment). At the stand level, changes in total QMD are a function of both diameter growth and mortality. To calculate the diameter increment in managed stands, the effects of mortality were removed. This was accomplished by removing trees from the calculation that did not survive the five year re-measurement period. This was different than the procedures used in the 1997 model, where the mortality affects were not removed.

Species groupings were assigned to each PSP measurement in both databases. Three groupings were identified; tolerant hardwood, intolerant hardwood and Aspen. Aspen was kept separate from the other intolerant hardwoods due to its unique characteristics. Plots were assigned to a group when more that 70% of the basal area was contained in the specified tree species (Table 5).

Table 5. Species group classification rules.

Species Group	Species Code	Species Common Name	Species Latin Name	Classification Rules
Tolerant	sM	Sugar Maple	*Acer saccharum*	sM+yB+Be Basal Area >= 70% of Total Basal Area
	yB	Yellow Birch	*Betula alleghaniensis*	
	Be	American Beech	*Fagus grandifolia*	
Intolerant	rM	Red Maple	*Acer rubrum*	rM+wB Basal Area >= 70% of Total Basal Area
	wB	White Birch	*Betula papyrifera*	
Aspen	tA	Trembling Aspen	*Populus tremuloides*	tA+lA Basal Area >= 70% of Total Basal Area
	lA	Largetooth Aspen	*Populus grandidentata*	

3.2 Research PSP Data Summaries

The compiled Research PSP database showed that 26% of the plot measurements were in a natural unmanaged condition while 74% were in managed plots (Figure 3). Of the managed plot measurements, 32% were in the precommercially thinned class, 67% were in the commercially thinned class and 1% fell in the 'other' class. Plots falling in the 'other' treatment class were primarily unevenaged trials or high grades which are not a part of the growth and yield model. Overall there were an adequate number of plots in all treatment groups for model development.

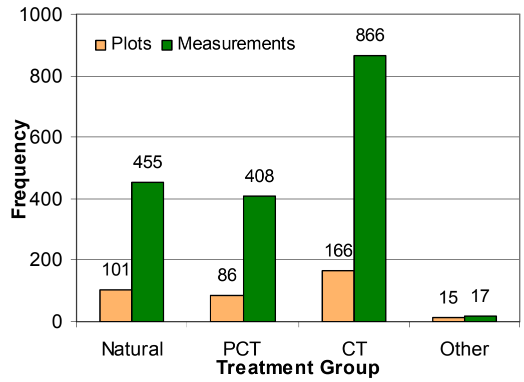


Figure 3. Research PSP plots and measurements distribution by treatment.

Species group distributions (Figure 4) showed the tolerant group to be more than two times the size of all other groups, representing 50% of all plot measurements. The intolerant group represented 20% and Aspen 9%. The remaining, 21% fell into the 'other' group that represented plots dominated by a different species or plots having a mix of tolerant and intolerant species. The uneven distribution among the species groups posed a challenge to species level model development. The low representation in the Aspen group stood out as a concern.

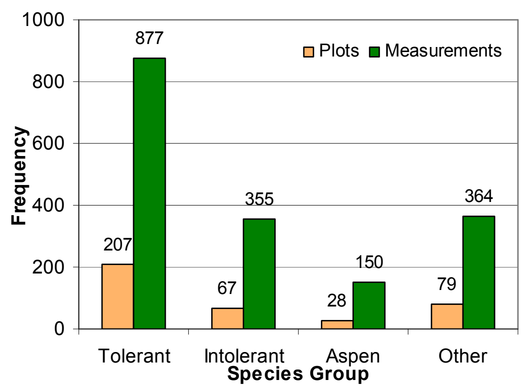


Figure 4. Research PSP plots and measurements distribution by species group.

Plot measurements were fairly well distributed across the primary site index classes (12m-21m) for both natural and treated stands (Figure 5).

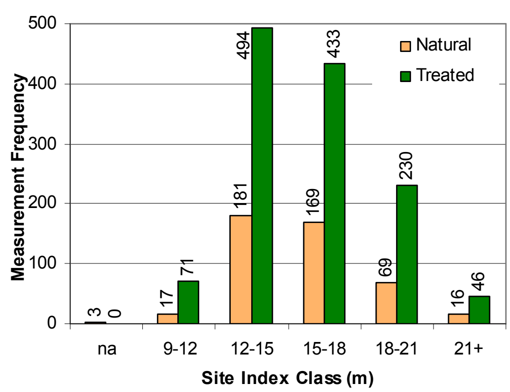


Figure 5. Research PSP measurement distribution by site index class and treatment.

Once the data were stratified by all three classifications (Treatment, Species Group and Site Index), more apparent limitations became obvious (Table 6). The grey colored cells in Table 6 highlight permutations where data are considered weak (less than 10 plot measurements), the pale yellow is considered fair (between 11-19 measurements), and the white is good (20+ measurements). The tolerant species group was the best represented with fair to good representation in all treatments across the main site index classes (12-21m). The intolerant group was lacking representation in the higher site index classes yet had good representation in all treatment classes. The Aspen group had relatively weak representation in most site index and treatment classes, except for the PCT class.

Table 6. Research PSP treatment and site index distributions summarized by species group.

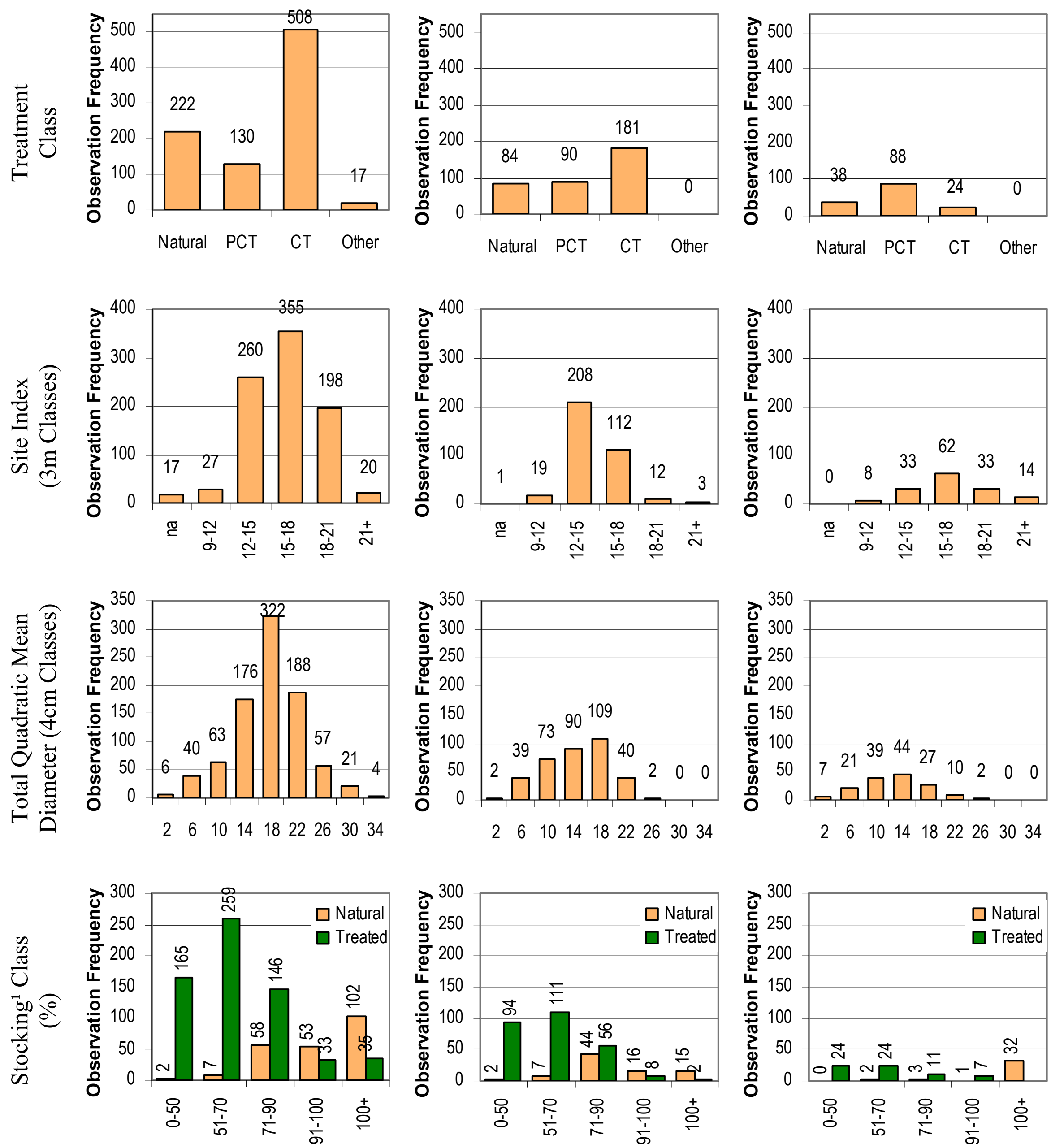
Treatment Class	Site Index Class (m)	Species Group Tolerant	Intolerant	Aspen	Other	Total
Natural	na	1	1	0	1	**3**
	9-12	3	8	0	6	**17**
	12-15	65	50	6	60	**181**
	15-18	114	18	19	18	**169**
	18-21	37	5	10	17	**69**
	21+	2	2	3	9	**16**
	Sub- Total	***222***	***84***	***38***	***111***	***455***
PCT	9-12	18	10	6	19	**53**
	12-15	41	61	17	19	**138**
	15-18	43	15	34	22	**114**
	18-21	20	3	20	23	**66**
	21+	8	1	11	17	**37**
	Sub- Total	***130***	***90***	***88***	***100***	***408***
CT	9-12	6	1	2	9	**18**
	12-15	154	97	10	95	**356**
	15-18	198	79	9	33	**319**
	18-21	141	4	3	16	**164**
	21+	9	0	0	0	**9**
	Sub- Total	***508***	***181***	***24***	***153***	***866***
Grand Total[1]		**860**	**355**	**150**	**364**	**[1]1729**

Note: 1) Grand total is 17 plots less than the total (1746) because the 'other' treatment class was excluded from the summary.

Table 7 contains a series of charts that compliment the numeric values presented in Table 6. In addition Table 7 shows the distribution of observations by DBH and stocking class. Representation across the DBH classes was good for the tolerant species group yet the intolerant and Aspen groups lacked good representation in the larger diameter classes. The stocking class distribution showed natural plots were primarily >=90% stocked, the exception being natural intolerant plots that were mostly in a lower stocking class. This was mainly an artifact of the 1997 model, which was not species specific. The distribution of treated plots fell primarily in classes less than maximum stocking. A small percentage of plots were >=90% stocked indicating some of the treated stands are approaching full stocking.

Table 7. Research PSP treatment, site index, diameter and stocking distributions by species group.

	Species Group		
	Tolerant	Intolerant	Aspen



1) Stocking was determined as the fraction of plot basal area to maximum basal area derived from the 1997 density function (F05).

3.3 Inventory PSP Data Summaries

Compiled Inventory PSP data showed an uneven distribution of plots among the species groups (Figure 6). Representation of plot measurements in the tolerant and intolerant groups were comparable (23% and 28% respectively) while the Aspen group only accounted for 2% of plot measurements. The 'other' species group represented the majority of plot measurements (46%) suggesting mixtures are a prevalent condition in the hardwood forests of the province.

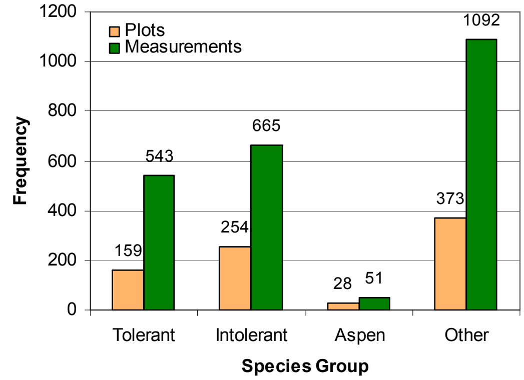


Figure 6. Inventory PSP plots and measurements distribution by species group.

The distribution across site index classes within the compiled Inventory PSP data showed good representation across the major site index classes (Figure 7). The distribution was similar to that observed in the Research PSP data (Figure 5).

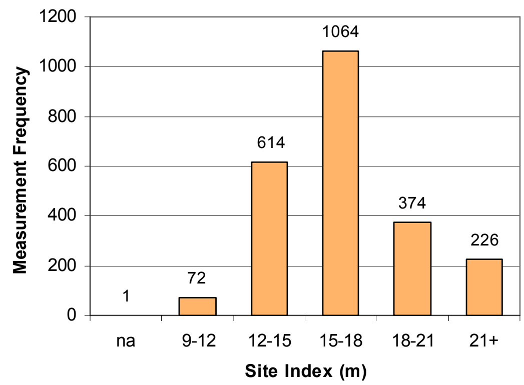


Figure 7. Inventory PSP plot measurement distribution by site index class.

Summarizing the Inventory PSP data by stocking class revealed the database is skewed away from the fully stocked condition (Figure 8). This picture is very different from the Research PSP data where the majority of observations from natural stands are at maximum stocking. This highlights one of the predominant reasons that the Inventory PSP data could not be used for model development. Even the proportions that seem fully stocked fail to meet other model criteria. Plots with high basal area also typically had large variations in diameters, high softwood content, and often multiple species groups all of which depart from the founding assumptions of the model.

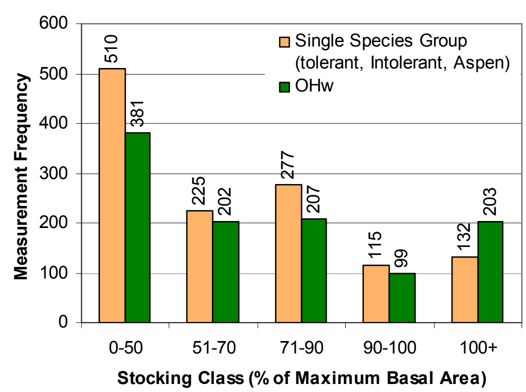


Figure 8. Inventory PSP plot measurement distribution by stocking class and species group.

Stratifying the species group and site index data observations by stocking classes showed limited representation of fully stocked stands (Table 8). In Table 8, the grey colored cells highlight permutations where data was considered weak (less than 10 plot measurements), the pale yellow was considered fair (between 11-19 measurements) and the white was good (20+ measurements). With no consideration for stocking, there was weak to fair representation in the Aspen group across all site index classes. By filtering data to those that were >=90% stocked, the entire Aspen group fell into the weak class and the representation in the tolerant and intolerant groups were dramatically reduced (by 77% and 83% respectively). Further filtering to stands that were >= 100% stocked, the observations were reduced by approximately 50% again and more fell below what would be considered good representation. Table 9 contains a series of charts that graphically illustrate the numeric values presented in Table 8.

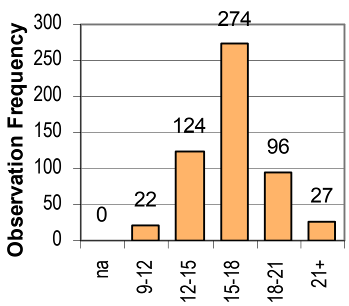
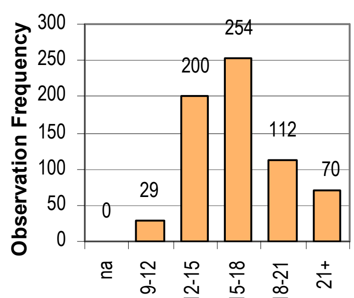
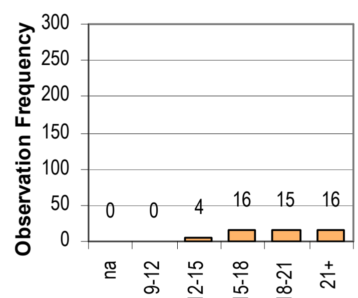
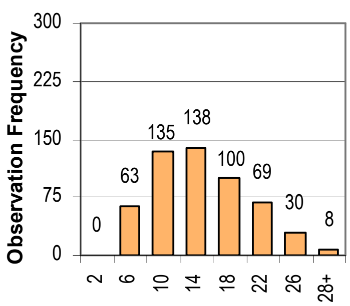
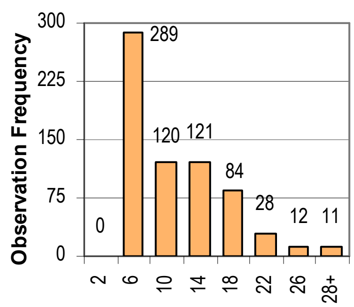
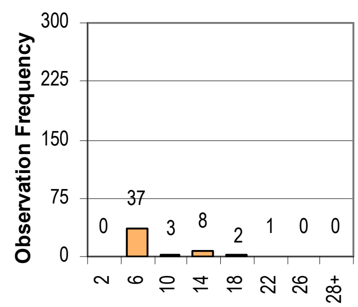
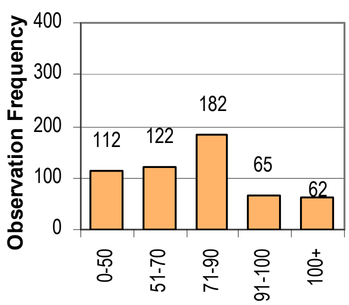
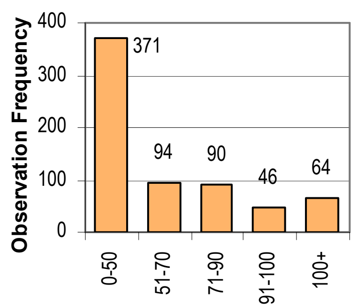
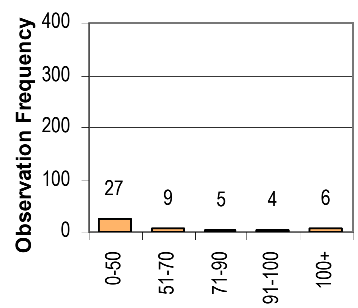
The limited number of plots that meet the requirements for model development (i.e. single species, fully stocked) was the primary reason that the Inventory PSP data was not used to augment the Research PSP database. The Inventory PSP database was used for the purpose of model validation.

Table 8. Inventory PSP site index distributions summarized by species group and stocking class grouping.

Stock -ing	Site Index (3m Classes)	Species Group Tolerant	Intolerant	Aspen	Other	Total
All Stocking[1] Classes	na	0	0	0	1	**1**
	9-12	22	29	0	21	**72**
	12-15	124	200	4	286	**614**
	15-18	274	254	16	520	**1064**
	18-21	96	112	15	151	**374**
	21+	27	70	16	113	**226**
	Total	**543**	**665**	**51**	**1092**	**2351**
Stocking[1] Classes >= 90%	na	0	0	0	0	**0**
	9-12	8	0	0	1	**9**
	12-15	26	22	1	56	**105**
	15-18	63	52	2	195	**312**
	18-21	28	21	1	41	**91**
	21+	2	15	6	9	**32**
	Total	**127**	**110**	**10**	**302**	**549**
Stocking[1] Classes >= 100%	na	0	0	0	0	**0**
	9-12	6	0	0	0	**6**
	12-15	13	12	0	33	**58**
	15-18	31	30	0	136	**197**
	18-21	11	14	1	27	**53**
	21+	1	8	5	7	**21**
	Total	**62**	**64**	**6**	**203**	**335**

1) Stocking was determined a as fraction of plot basal area to maximum basal area derived from the 1997 density function (F05).

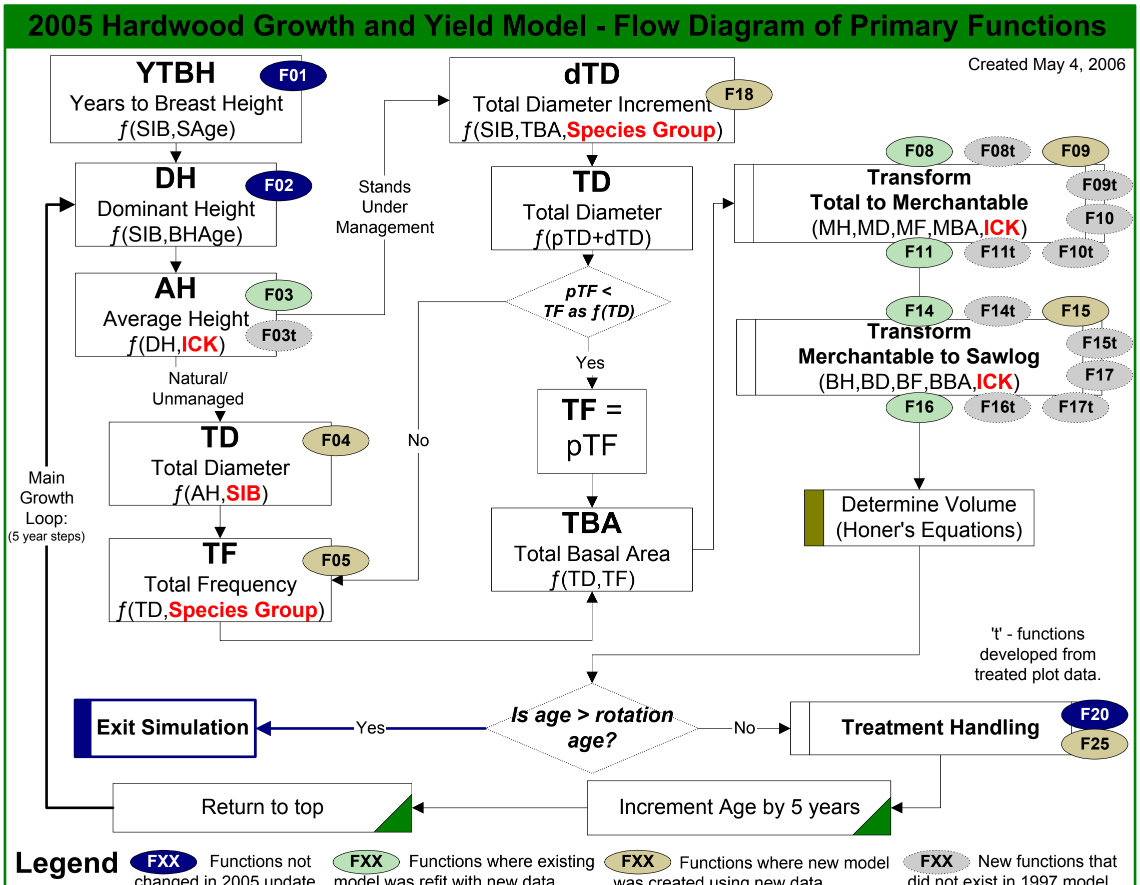
Table 9. Inventory PSP site index, diameter and stocking distributions by species group.

	Species Group		
	Tolerant	**Intolerant**	**Aspen**
Site Index (3m Classes)			
Total Quadratic Mean Diameter (4cm Classes)			
Stocking[1] Class (BA as % of fully stocked BA)			

1) Stocking was determined a as fraction of plot basal area to maximum basal area derived from the 1997 density function (F05).

4 Model Development / Update

The 2005 model update revisited 11 of the original 14 functions used in the 1997 model. In addition to the existing 14 functions, 11 new functions were created (Figure 9) for a total of 25 in the new model. The new model is referred to as the 2005 model. Figure 9 and Table 10 provide a summary of the 2005 model and its associated functions.



Code	Units	Description	Code	Units	Description
SAge	years	Stump Age	MH	m	Merchantable (dbh >=9.1cm) Avg. Height
BHAge	years	Breast Height Age	MD	cm	Merchantable Diameter at Breast Height
SIB	m	Site Index @50yrs (Breast Height Age)	MF	stems/ha	Merchantable Frequency
YTBH	years	Years to Breast Height	MBA	m²/ha	Merchantable Basal Area
DH	m	Dominant Height	BH	m	Sawlog (dbh >=25.4cm) Avg. Height
AH	m	Average Total Height	BD	cm	Sawlog Diameter at Breast Height
TD	cm	Total Diameter at Breast Height	BF	stems/ha	Sawlog Frequency
TF	stems/ha	Total Frequency	BBA	m²/ha	Sawlog Basal Area
TBA	m²/ha	Total Basal Area	pTD	cm	Total Diameter in Previous Period
dTD	cm	Total Diameter Increment (5yr) (Treated)	pTF	stems/ha	Total Frequency in Previous Period
ICK	na	Treatment Flag	Red Text		New variables added in 2005 update

Figure 9. Hardwood Growth and Yield model flow diagram highlighting functions updated in the 2005 model.

Table 10. Functions used in the 2005 hardwood growth and yield model.

Code	Model	Coefficients						Dummy Variables			
		ß0	ß1	ß2	ß3	ß4	ß5	No.	Grouping	n	r²
F01	$YTBH = \beta0 - \beta1*SIB+\beta2*SIB^{\beta3}$										
		10.5513	0.7565	0.0339	1.7826	N/A	N/A	N/A	N/A	N/A	N/A
F02	DH = See 1997 Model										
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F03	AH = ß0+ß1*DH										
		-0.7520	0.9654	N/A	N/A	N/A	N/A	N/A	N/A	439	0.975
F03t	AH = ß0+ß1*DH										
		-0.3979	0.9620	N/A	N/A	N/A	N/A	N/A	N/A	1274	0.985
F04	$TD = (\beta0+\beta1*SIB)*AH^{(\beta2+\beta3*SIB)}$										
		0.3068	0.0004	1.6713	-0.0171	N/A	N/A	N/A	N/A	438	0.841
F05	$TF = 10^{(\beta0+\beta1*Log10(TD)+(\beta2*dV1+\beta3*dV2))}$										
		5.1557	-1.6880	0.0490	0.1169	N/A	N/A	2	Tolerant (1,0) Aspen (0,1) Intolerant (0,0)	320	0.954
F08	$MHrat = (1+e^{\beta0*TD})^{\beta1}$										
		-0.2035	0.5109	N/A	N/A	N/A	N/A	N/A	N/A	431	0.818
F08t	$MHrat = (1+e^{\beta0*TD})^{\beta1}$										
		-0.2988	0.8409	N/A	N/A	N/A	N/A	N/A	N/A	1242	0.763
F09	$MDrat = (1+e^{\beta0*TD})^{\beta1}$										
		-0.2095	2.5161	N/A	N/A	N/A	N/A	N/A	N/A	432	0.868
F09t	$MDrat = (1+e^{\beta0*TD})^{\beta1}$										
		-0.3004	3.3287	N/A	N/A	N/A	N/A	N/A	N/A	1242	0.873
F10	$MFrat = (1-e^{\beta0*TD})^{\beta1}$										
		-0.2017	5.8364	N/A	N/A	N/A	N/A	N/A	N/A	437	0.841
F10t	$MFrat = (1-e^{\beta0*TD})^{\beta1}$										
		-0.3527	20.3227	N/A	N/A	N/A	N/A	N/A	N/A	1242	0.896
F11	$MBArat = (1-e^{\beta0*TD})^{\beta1}$										
		-0.3383	7.4422	N/A	N/A	N/A	N/A	N/A	N/A	437	0.904
F11t	$MBArat = (1-e^{\beta0*TD})^{\beta1}$										
		-0.5321	57.3920	N/A	N/A	N/A	N/A	N/A	N/A	1242	0.970
F14	$BHrat = (1+e^{\beta0*MD})^{\beta1}$										
		-0.0883	0.5563	N/A	N/A	N/A	N/A	N/A	N/A	173	0.162
F14t	$BHrat = (1+e^{\beta0*MD})^{\beta1}$										
		-0.1163	0.7595	N/A	N/A	N/A	N/A	N/A	N/A	722	0.246
F15	$BDrat = (1+e^{\beta0*MD})^{\beta1}$										
		-0.0682	1.8245	N/A	N/A	N/A	N/A	N/A	N/A	177	0.177
F15t	$BDrat = (1+e^{\beta0*MD})^{\beta1}$										
		-0.1104	3.5178	N/A	N/A	N/A	N/A	N/A	N/A	722	0.642
F16	$BBArat = (1-e^{\beta0*MD})^{\beta1}$										
		-0.1463	21.3988	N/A	N/A	N/A	N/A	N/A	N/A	177	0.671
F16t	$BBArat = (1-e^{\beta0*MD})^{\beta1}$										
		-0.1769	44.4532	N/A	N/A	N/A	N/A	N/A	N/A	722	0.768
F17	$BFrat = (1-e^{\beta0*MD})^{\beta1}$										
		-0.1128	18.0107	N/A	N/A	N/A	N/A	N/A	N/A	177	0.786
F17t	$BFrat = (1-e^{\beta0*MD})^{\beta1}$										
		-0.1556	45.8779	N/A	N/A	N/A	N/A	N/A	N/A	722	0.895
F18	$\Delta TD = (\beta0+\beta1*SIB)*e^{(\beta2+\beta3*SIB)*TBA}+\beta4*dV1+\beta5*dV2$										
		0.6636	0.0971	-0.0625	0.0005	0.3062	0.5154	2	Tolerant (1,0) Aspen (0,1) Intolerant (0,0)	816	0.639
F20	AI-TD-CT = ß0+ß1*TD+ß2*BArem										
		2.2040	1.0660	0.0180	N/A	N/A	N/A	N/A	N/A	187	0.481
F25	AI-TD-PCT = ß0+ß1*TD+ß2*SP										
		-0.6680	0.2610	0.4560	N/A	N/A	N/A	N/A	N/A	25	.324

Note: 'dv' = Dummy Variable; 't' = Signifies Functions Developed for Treated Stands

In the 2005 model, the 'Years to Breast Height' (F01) and 'Dominant Height' (F02) functions were left unchanged since they were developed from a specific stem analysis database that has not been updated (NSDNR, 1987). Likewise, the treatment handling function F20 was based on specific data (measured artificial increase in total diameter following commercial thinning) and, therefore, was not updated.

Of the 11 new functions added (F03t, F08t, F09t, F10, F10t, F11t, F14t, F15t, F16t, F17, F17t), nine of them captured stand level development patterns in treated stands while the remaining two (F10, F17) complimented existing conversion functions. The new 'treatment based' functions used the same model form as the natural counterpart yet were fitted to treated data (also referred to as managed) rather than to data from natural unmanaged stands.

Of the 11 original functions updated, five (F03, F08, F11, F14, F16) were fit to new data using the original model while the other six (F04, F05, F09, F15, F18, F25) were updated with a new model and/or new variables. The natural stand diameter model (F04) was changed to incorporate the site index variable while the stand density model (F05) and the treated stand diameter model (F18) were both changed to incorporate the species group variable. The PCT artificial increase function (F25) was changed to predict change in diameter rather than new diameter. The total to merchantable (F09) and merchantable to sawlog (F15) diameter functions were changed to ratio models similar to the other conversion functions (F08, F11, F14, F16).

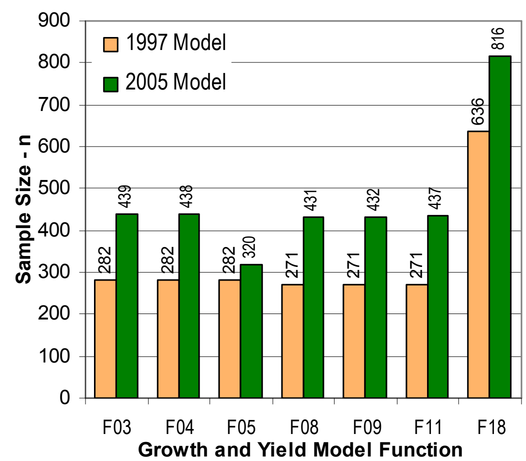


Figure 10. Sample size changes from the 1997 model by function.

The sample size of most revisited functions increased by approximately 55% to 65% (Figure 10). The exceptions were the total density function (F05) and the managed stand diameter function (F18) where plots available for model development increased by 14% and 28% respectively. This was because 177 plot measurements were culled since they fell into the 'Other – Mixed' species group. The 1997 model used all plots irrespective of species group.

The larger data sets resulted in similar or better r^2 scores across all updated functions (Figure 11). The sawlog conversion functions were not comparable to those of the 1997 model as the 2005 model used a new sawlog specification[3].

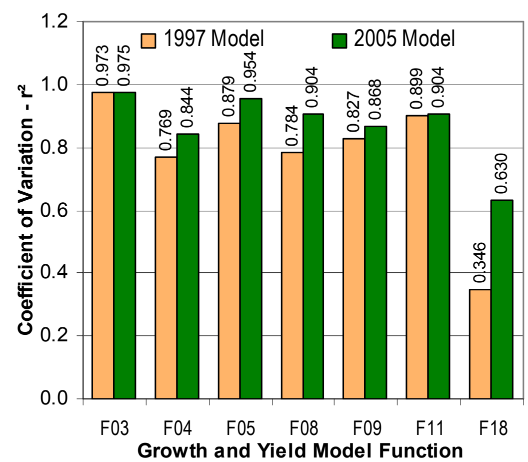


Figure 11. Coefficient of variation (r^2) changes from the 1997 model by function.

[3] The 2005 sawlog specification was 25.4cm DBH and 20.32cm top versus a 15.24cm DBH and 10.16cm top in the 1997 model.

The following sections describe in more detail the development of each new function. Each function has its own section (4.1 to 4.5) except for the conversion functions that are combined into two sections (4.6 and 4.7).

4.1 F03(t) – Average Height as ƒ(Dominant Height)

In 1997 a linear model was used to predict average total stand height (AH) from dominant height (DH) (average height of 5 tallest trees). The 1997 model used a single function for both managed and unmanaged stands. In the 2005 update separate functions were developed (F03 and F03t). For both functions it was found that the linear model ($AH = ß0 + ß1*DH$) used in 1997 was still the best model for the data.

For the natural unmanaged function (F03), there were 455 plot measurements potentially available for model development. Preliminary analysis of the observations resulted in the removal of 16 outliers. This left 439 observations which represented a 56% increase over the number of observations used in 1997 (282 observations).

Figure 12 shows the 2005 AH function plotted with the data observations and the original 1997 function. The model fit the data well with an r^2 of .975 which was a slight increase from the 1997 model (0.973). In comparison to the 1997 model, the updated function resulted in little to no change in predictions.

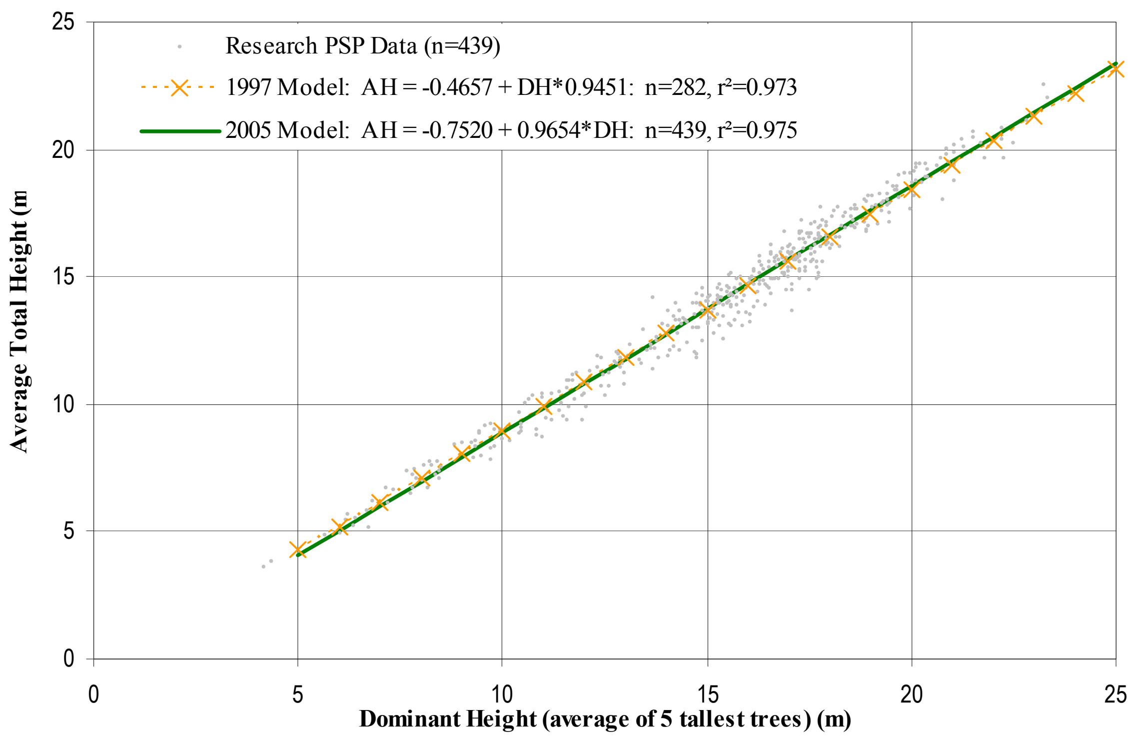


Figure 12. 2005 average total height function (F03) for natural unmanaged stands.

For the managed stand function (F03t) all of the 1274 plot measurements from managed stands were used. Figure 13 shows the 2005 AH function for managed stands plotted with the data observations and the natural unmanaged function (the 1997 and 2005 functions). The model fit the data well with an r^2 of .985 which was a slight increase over the natural unmanaged function (0.975). The treated stand function showed a slight increase (~.3m) from the natural across all dominant heights. As a percentage, the difference ranged from an 8% increase for young stands (DH=5m) to a 1% increase for the tallest stands (DH=25m).

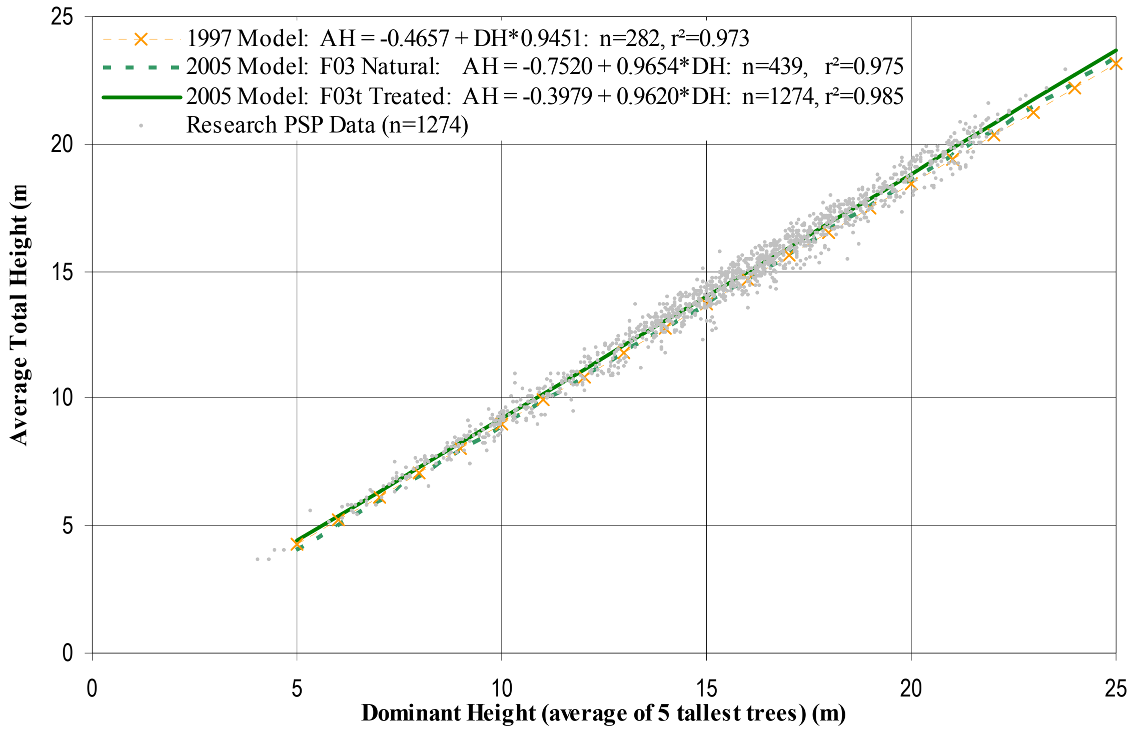


Figure 13. 2005 average total height function (F03t) for managed stands (PCT/CT).

4.2 F04 – Total Diameter as ƒ(Average Height, Site Index)

The 1997 model used a power function to predict total quadratic mean diameter (TD) from average total height (AH). The 2005 update found the power model still gave the best fit to the data however there was a high level of variation about the function.

Exploration of the data showed that site index could explain much of the observed variation. Observations from the poorer sites tended to show larger diameters in comparison to the better sites for any given height. Consequently, the model was modified to incorporate a site index variable (SIB) (Table 11).

Analysis of the observations for outliers resulted in the removal of 17 outliers leaving 438 data observations for model development. This represented a 55% increase in observations from 1997 (282 observations).

Table 11. Summary of the updated total diameter model (F04) for natural unmanaged stands.

Attribute	1997 Model	2005 Model
Sample Size	282	438
Model Form	$TD = ß0*AH^{ß1}$	$TD = (ß0+ß1*SIB)*AH^{(ß2+ß3*SIB)}$
Parameters		
ß0	0.357182	0.306814
ß1	1.338085	0.000443
ß2	---	1.671265
ß3	---	-0.0171
r^2	0.769	0.841

Figure 14 shows the 2005 TD function (F04) plotted using five site index values with the data observations and the original 1997 function. The model fit the data well with an r^2 of 0.841 which was a slight increase over the 1997 model (0.769). More importantly the model better captured the site variation observed in the data. The middle site index class (15-18m; midpoint 16.5m) fit closely to the 1997 function yet, the main difference was that an increase or decrease in site index inversely affected predicted total diameter.

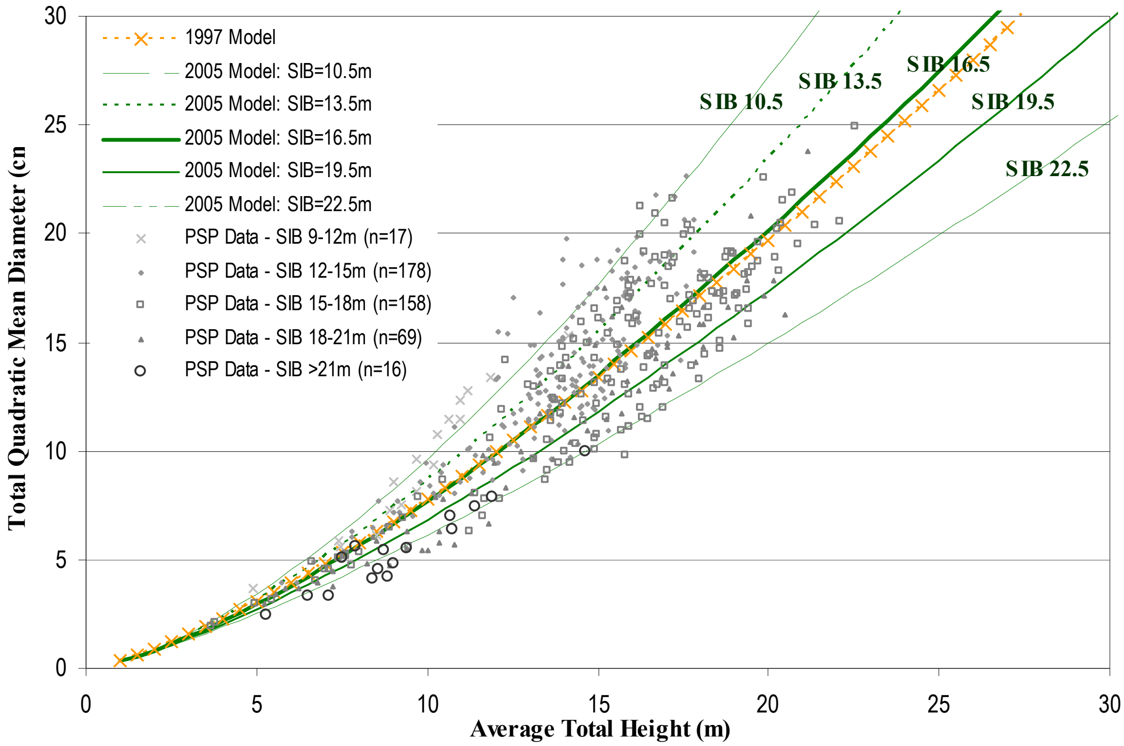


Figure 14. 2005 total diameter function (F04) for natural unmanaged stands.

4.3 F05 – Total Frequency as ƒ(Total Diameter, Species Group)

The 1997 model was a linear model fit to log transformed data that predicted total density (TF) from total quadratic mean diameter (TD). Exploratory analysis using both linear and nonlinear models showed the linear model was still the best model for the data. The analysis additionally showed that more of the observed variation could be explained through the species group variable. The selected model was the same as the one used in 1997 yet it was modified to incorporate species group by using 'dummy' variables.

Preliminary analysis of the observations resulted in the removal of 43 outliers. An additional 92 observations were removed because they fell in the 'Other-Mixed' species group. This left 320 (of the 455) plot measurements available for model development which was a 13% increase over the number of observations used in 1997 (282 observations).

The 2005 model used 'dummy' variables (SPSS, 1999) to incorporate the species group variable into the model. Two 'dummy' variables allowed each of the species groups to be distinguished within a single regression model. Each species group was arbitrarily assigned a binary combination of values (Table 12).

Table 12. Summary of the updated total density model (F05).

Attribute	1997 Model	2005 Model
Sample Size	282	320
Model Form	LOG(TF) = ß0+ß1LOG(TD)	LOG(TF) = ß0+ß1LOG(TD)+(ß2*DV1+ß3*DV2)
Parameters		
ß0	5.126578	5.155702
ß1	-1.611001	-1.68804
ß2	---	0.048983
ß3	---	0.116856
Species Group Dummy Variables		
Tolerant	---	DV1 = 1, DV2 = 0
Aspen	---	DV1 = 0, DV2 = 1
Intolerant	---	DV1 = 0, DV2 = 0
r^2	0.879	0.954

Note 'LOG' refers to log base 10.

Figure 15 shows the 2005 TF function plotted on log-log scale by species group with the data observations and the original 1997 function. Figure 16 shows the same chart on a standard scale. Overall, the model fit the data well with an r^2 of .954 which was a 9% increase from the 1997 model (0.879). The tolerant species group showed little change from the 1997 model in the 6cm to 20cm diameter range. In comparison, the Aspen density predictions were higher while the intolerant were lower for any given diameter. The Aspen and intolerant groups lacked data in the larger diameter classes. Between the two groups, there were only two plots having a total diameter greater than 20cm. This is likely due to the onset of mortality in these species groups before the larger diameters are reached.

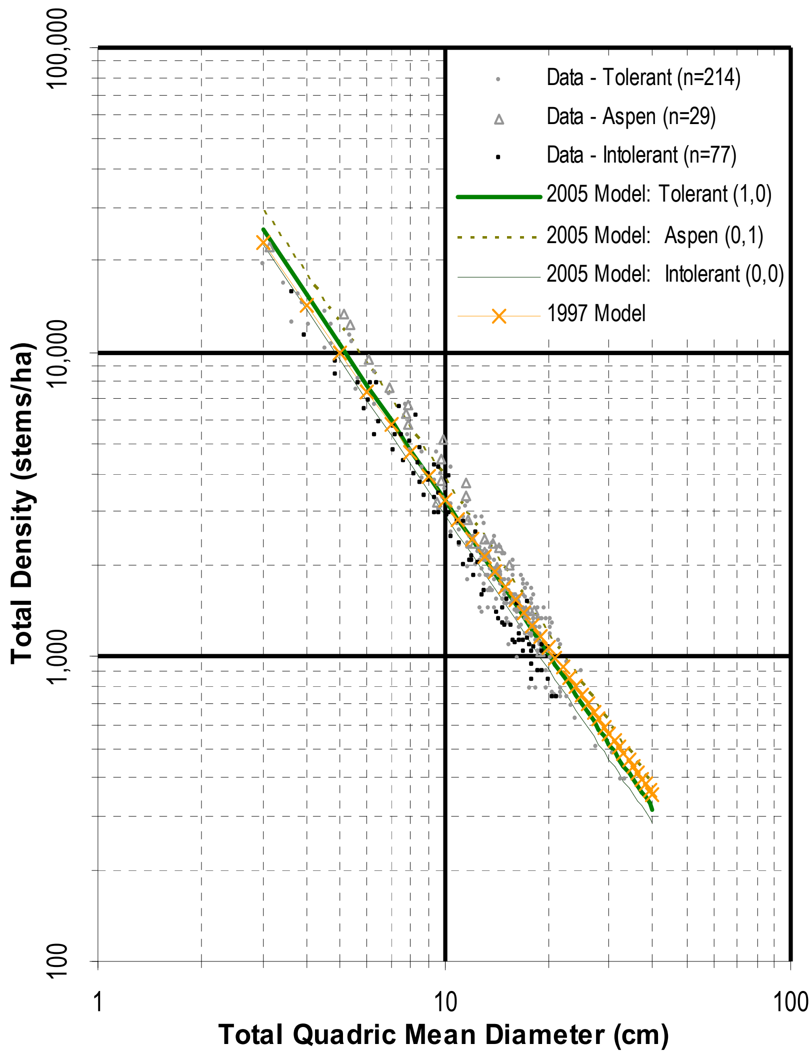


Figure 15. 2005 total density function (F05) plotted log-log with species group variables.

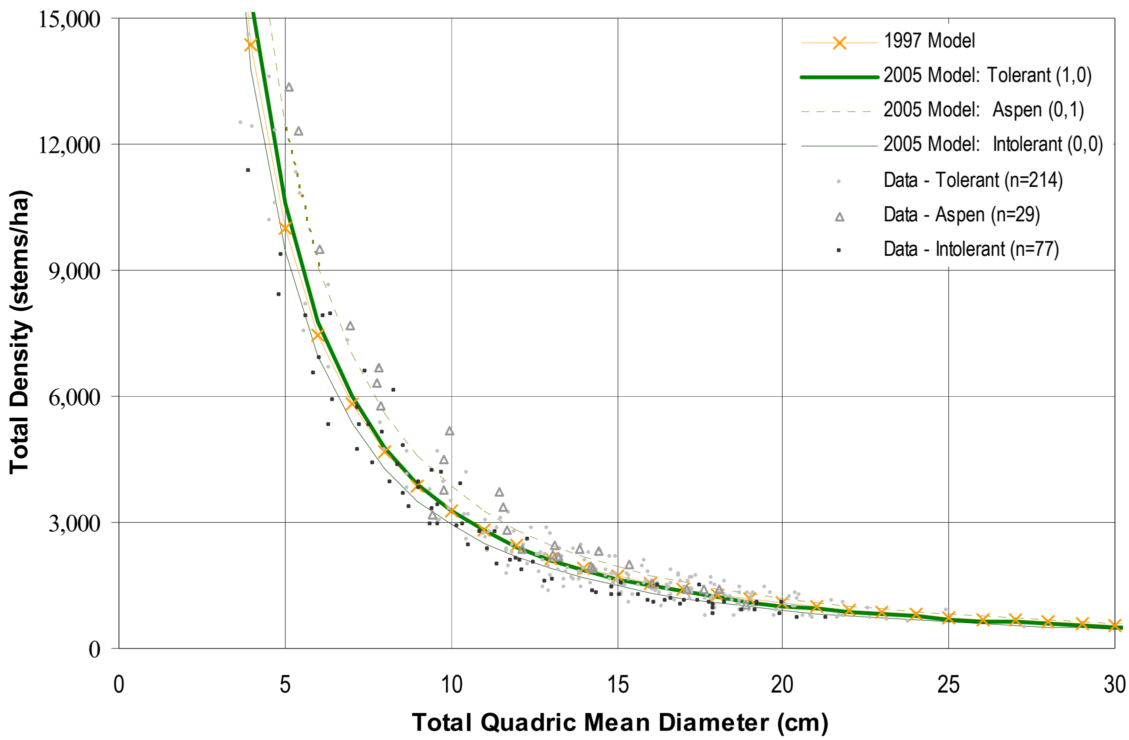


Figure 16. 2005 total density function (F05) plotted with species group variables.

4.4 F18 – Diameter Increment as ƒ(Initial Basal Area, Site Index, Species Group)

The managed stand diameter increment function (F18) used the same exponential model form as the 1997 model. In addition to the existing total basal area (TBA) and site index (SIB) variables, the 2005 update incorporated species groups through the use of 'dummy' variables.

The diameter increment function used plot measurements from precommercially and commercially thinned stands. After the 1,274 plot measurements available were compiled for diameter increment (i.e. 5 year change in TD between a pair of plot measurements), the data observations were reduced to 993 measurements. In addition the 'Other-Mixed' species group plots (179) were removed leaving 816 plot measurements for model development.

Table 13 shows the 1997 model along with the 2005 model. The two dummy variables added (DV1 and DV2) allowed the tolerant, intolerant and Aspen species groups to be incorporated. The model is difficult to present graphically since the predicted diameter increments have two independent variables (TBA and SIB). Figure 17 to Figure 21 break the database into five site index classes and plot the midpoint of each class by species group. Overall the new model represents a significant improvement from 1997 accounting for a far larger percentage of the observed variation (r^2 score increased by 85%).

Predicted diameter increments were lower in the 2005 model. The main reason was due to the modified data compilation methods that separated the portion of diameter increment caused by mortality as described in the data compilation section (Section 3.1). This affected the higher basal area predictions more so than the lower because mortality was more of a factor at higher basal areas. The 2005 tolerant and 1997 model for the 15-18m site index class (Figure 19) is a good illustration of this trend. At a TBA of 25m²/ha the 2005 model (SIB=16.5m, Tolerant Species Group) predicted 20% less (1.11cm vs. 0.89cm) diameter increment than the 1997 model did.

In terms of species grouping, the model seemed to perform well where there was adequate data. In general the tolerant group occupied the middle ground with the Aspen diameter increment predictions being consistently higher and the intolerants being lower for any given basal area and site index. Although the functions behaved as expected there was significantly less representation in the intolerant and Aspen species groups. This resulted in less confidence in these species groups. In particular, the lack of observations having site indices greater than 18m in the intolerant group added uncertainty for predictions at the higher site indices. Although the Aspen had fewer observations they were better distributed across the range of site indices.

Table 13. Summary of updated managed stand diameter increment model (F18).

Attribute	1997 Model	2005 Model
Sample Size	636	816
Model Form	$\Delta TD = (ß0+SIB*ß1)*e^{(ß2+SIB*ß3)*TBA}$	$\Delta TD = (ß0+SIB*ß1)*e^{(ß2+SIB*ß3)*TBA}+ß4*dV1+ß5*dV2$
Parameters		
ß0	-0.71788	0.663631
ß1	0.183536	0.097132
ß2	-0.00615	-0.06252
ß3	-0.00141	0.000496
ß4	---	0.306196
ß5	---	0.515384
Species Group Dummy Variables		
Tolerant	---	DV1 = 1, DV2 = 0
Aspen	---	DV1 = 0, DV2 = 1
Intolerant	---	DV1 = 0, DV2 = 0
r^2	0.346	0.639

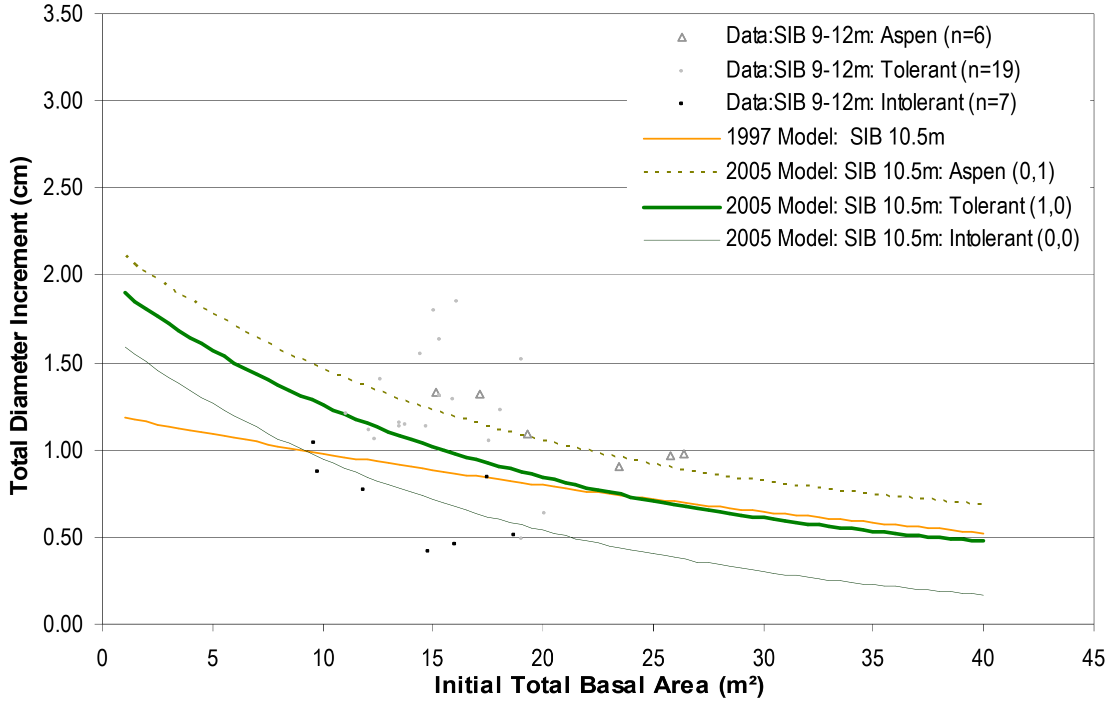


Figure 17. 2005 managed stand diameter increment function (F18) for the 9-12m site index class.

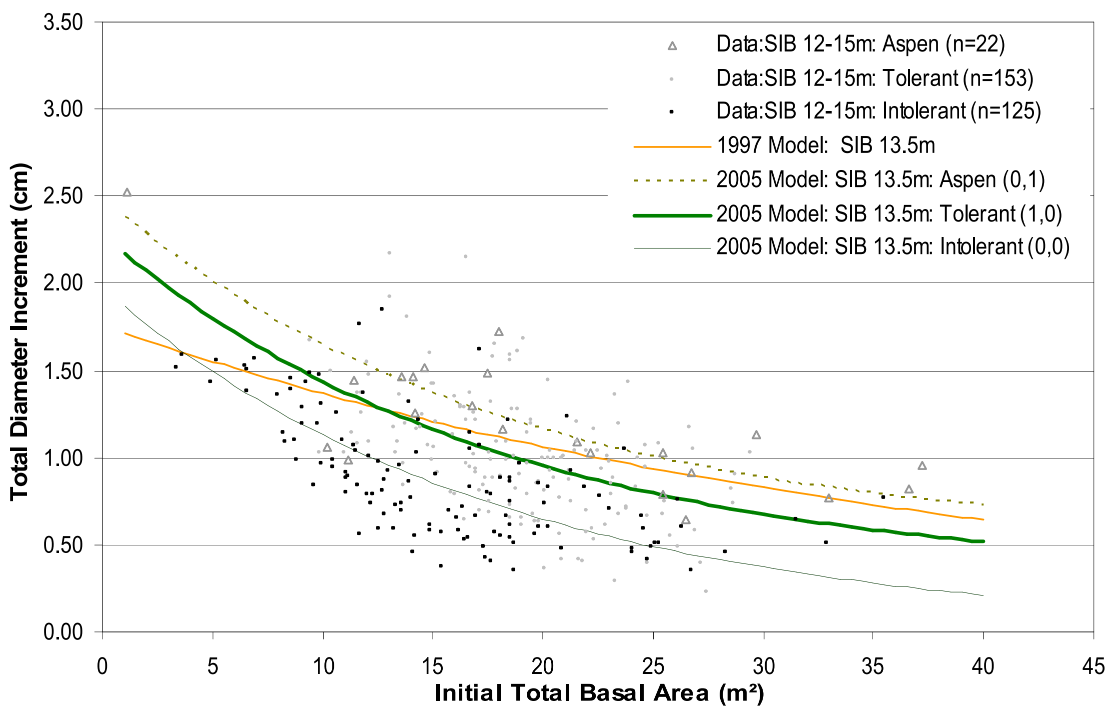


Figure 18. 2005 managed stand diameter increment function (F18) for the 12-15m site index class.

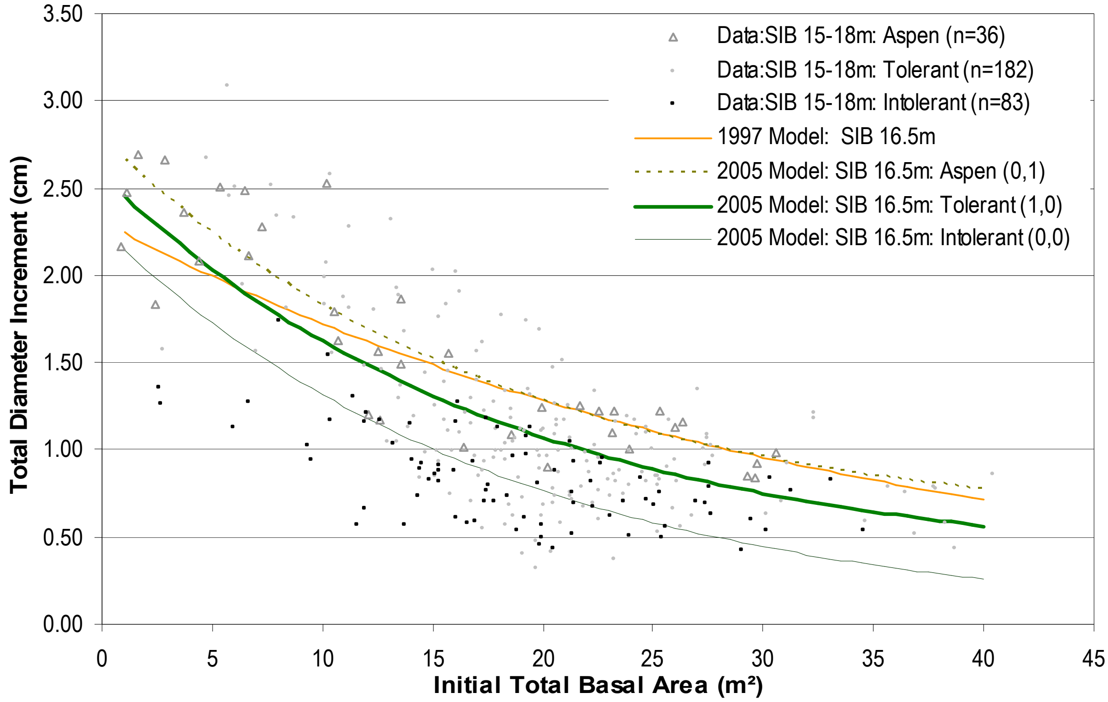


Figure 19. 2005 managed stand diameter increment function (F18) for the 15-18m site index class.

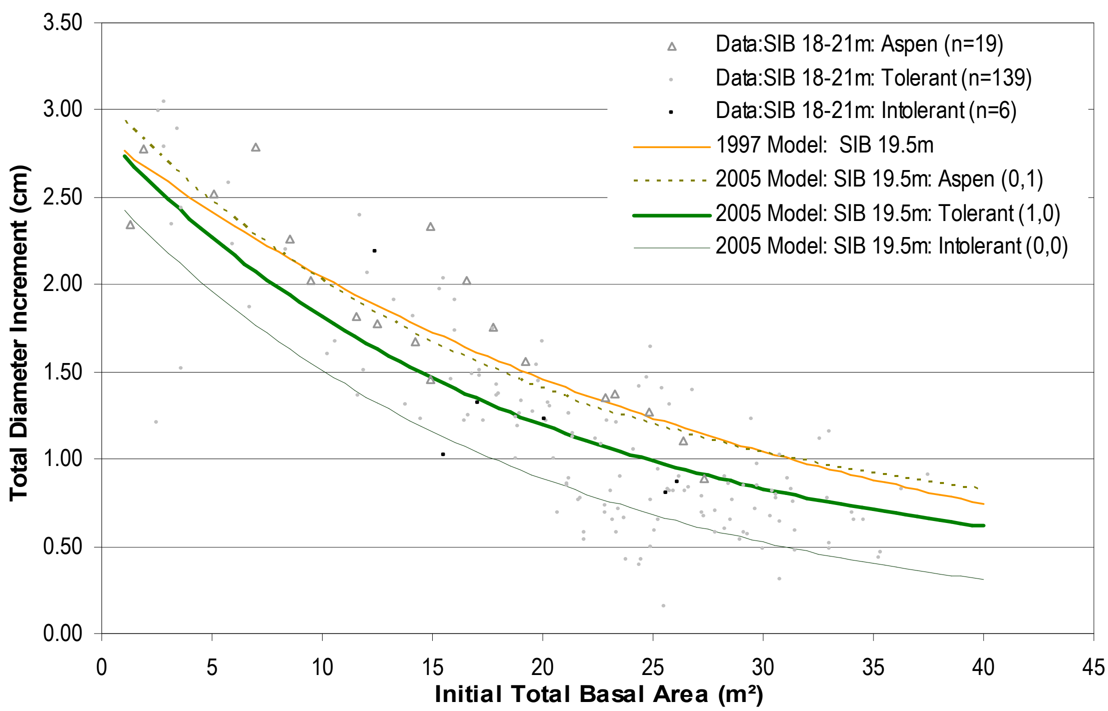


Figure 20. 2005 managed stand diameter increment function (F18) for the 18-21m site index class.

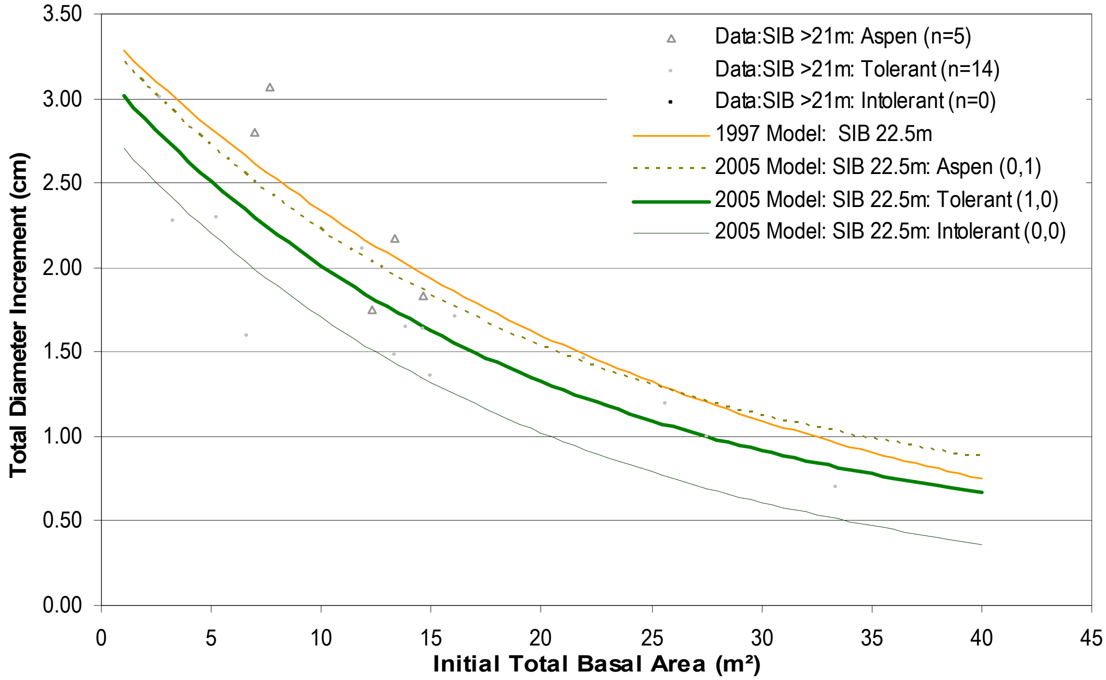


Figure 21. 2005 managed stand diameter increment function (F18) plotted for the 21m plus site index class.

4.5 F25 – Artificial Diameter Increase as ƒ(Total Diameter, Spacing)

In 1997 a linear model was used to predict the artificial increase in total diameter (AI-TD-PCT) following a precommercial thinning from the pre-treatment total diameter and the treatment spacing. The 2005 update confirmed the linear model used in 1997 was still the best model for the data. A key change in the 2005 model was that the model was fit to the observed change in diameter rather than simply the post-treatment diameter.

For the AI-TD-PCT function (F25) there were 25 observations available for model development. An observation represented the total diameter difference (in cm) between the pre and post-treatment measurements. Since the data was from spacing trials, the pre-treatment diameter was taken from the controls. If there was more than one control plot established in a trial the controls were averaged. Similarly, the post-treatment total diameter was the total diameter from the treated stands which were also averaged if there were multiple plots at a given spacing within a trial. The AI-TD-PCT was the difference between the two.

Figure 22 shows the 2005 AI-TD-PCT function plotted by pre-treatment total diameter (TD) and treatment spacing with the 1997 function. Overall the model produced acceptable results that supported expected responses. The low r^2 value (0.324) is reflective of the small sample size combined with the inherent variation of using the trial data. Pre and post measurements within the same plot could reduce some of the observed variation. In comparison to the 1997 model; the updated function showed considerable change. The new function showed a reverse trend with pre-treatment diameter compared to the 1997 model. The trend with spacing was similar with less of a difference between spacings. The 2005 model showed a much better fit to observed data.

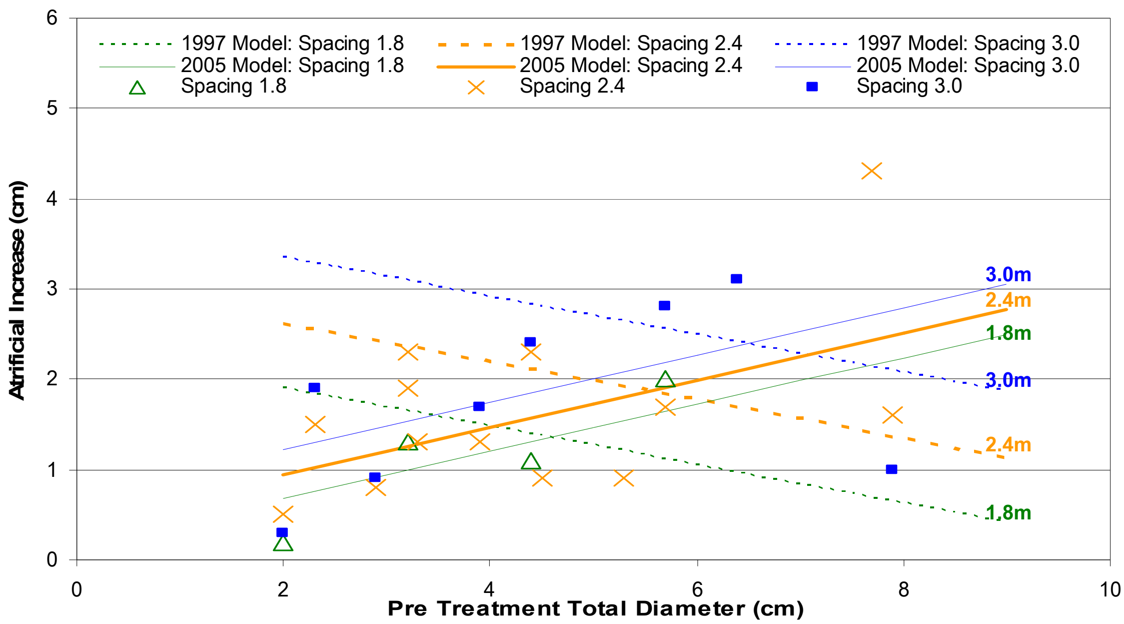


Figure 22. 2005 artificial increase function for precommercially thinned stands (F25) plotted by pre-treatment diameter (TD) and spacing.

4.6 F08(t),09(t),10(t),11(t) – Merchantable Conversion Ratio Functions

In the 1997 model, the conversion from total stand characteristics (height, diameter, density and basal area) to merchantable was accomplished by way of three functions that used total quadratic mean diameter (TD) as the independent variable. Two of the functions, F08 (height conversion) and F11 (basal area conversion), were ratio functions that predicted a fraction to apply against the total to derive the merchantable component. The diameter conversion function (F09) was a linear model that predicted merchantable diameter directly from total diameter.

In the 2005 update three major changes were made to the merchantable conversion functions. First, the diameter conversion function (F09) was changed to a ratio model (similar to the height and basal area models). Secondly, a duplicate set of functions were developed to predict the conversions for managed stands. This resulted in the creation of three new functions (F08t, F09t and F11t). Thirdly, a frequency conversion function was developed for managed and unmanaged stands (F10 and F10t). Table 14 gives a summary of the updated and new merchantable conversion functions.

Table 14. Summary of total to merchantable conversion functions.

Function	Attribute	1997 Model	2005 Model
F08			
	Sample Size	271	431
	Model Form	$MHrat = (1+e^{\beta0*TD})^{\beta1}$	$MHrat = (1+e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0	-0.1971	-0.20345
	ß1	0.4896	0.51093
	r^2	0.784	0.817
F08t			
	Sample Size		1242
	Model Form		$MHrat = (1+e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0		-0.29881
	ß1		0.840933
	r^2		0.763
F09			
	Sample Size	271	432
	Model Form	$MD = \beta0+\beta1*TD$	$MDrat = (1+e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0	5.9041	-0.2095
	ß1	0.7629	2.516098
	r^2	0.827	0.868
F09t			
	Sample Size		1242
	Model Form		$MDrat = (1+e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0		-0.30041
	ß1		3.328653
	r^2		0.873
F10			
	Sample Size		437
	Model Form		$MFrat = (1-e^{\beta0*TD})^{\beta1}$
	Parameters		
			-0.20168
			5.836399
	r^2		0.841
F10t			
	Sample Size		1242
	Model Form		$MFrat = (1-e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0		-0.35270
	ß1		20.322701
	r^2		0.896
F11			
	Sample Size	271	437
	Model Form	$MBArat = (1-e^{\beta0*TD})^{\beta1}$	$MBArat = (1-e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0	-0.3746	-0.33826
	ß1	10.8558	7.442224
	r^2	0.899	0.904
F11t			
	Sample Size		1242
	Model Form		$MBArat = (1-e^{\beta0*TD})^{\beta1}$
	Parameters		
	ß0		-0.5321
	ß1		57.39198
	r^2		0.970

All updated functions (F08, F09, F11) fit the data well. The r^2 value for each function increased in the 2005 model. Additionally, the five new functions (F08t, F09t, F10, F10t, F11t) had relatively high r^2 values indicating a good fit to the observed data.

The merchantable height function for natural stands produced nearly identical predictions as the 1997 model (Figure 23). However, the new function for managed stands (F08t) showed a much sharper transition in the predicted conversion ratio (Figure 24). This was because managed stands showed less height variability compared to natural stands. In addition, natural stands showed a more gradual transition of trees into the merchantable class.

The 2005 natural unmanaged merchantable diameter conversion function is similar to that of the 1997 model in the 10cm diameter range yet predictions separate as the diameter increases or decreases from that point (Figure 25). This was due to the new model being more flexible and, therefore, better fit the data, as supported by the improved r^2 values (0.827 vs. 0.868). Fitting the model to treated data mirrored the trend observed for the height conversion function. The function showed a shorter transition window reflecting the reduced diameter variability in the managed stand data (Figure 26).

The 2005 natural unmanaged merchantable frequency conversion function was created using a model similar to the other ratio functions. The function (F10) fit the data well with an r^2 of 0.841 (Table 14). The associated managed stand function (F10t) showed a sharper transition similar to the patterns observed in the other managed stand functions (F08t, F09t, F11t) (Figure 28).

The 2005 natural unmanaged basal area update refit the 1997 model to the new data. The updated function gave a slightly better r^2 score with predictions highly similar to the 1997 model (Figure 29). At the smaller diameters, there was some separation between predictions which is most likely due to the 60% increase in observations from 1997. The managed stand function (F11t) showed a sharper transition similar to the patterns observed in the other managed stand functions (F08t, F09t,F10t) (Figure 30).

Although conversions were developed for all four stand characteristics (height, diameter, frequency, and basal area) only three were utilized in the final model. Height, frequency and basal area were selected as they performed well together in the model testing and validation phases. The model uses merchantable frequency and basal area predictions to calculate merchantable diameter. The merchantable diameter conversion functions (F09, F09t, F10t) remain in the model and can be enabled for future development or testing as needed.

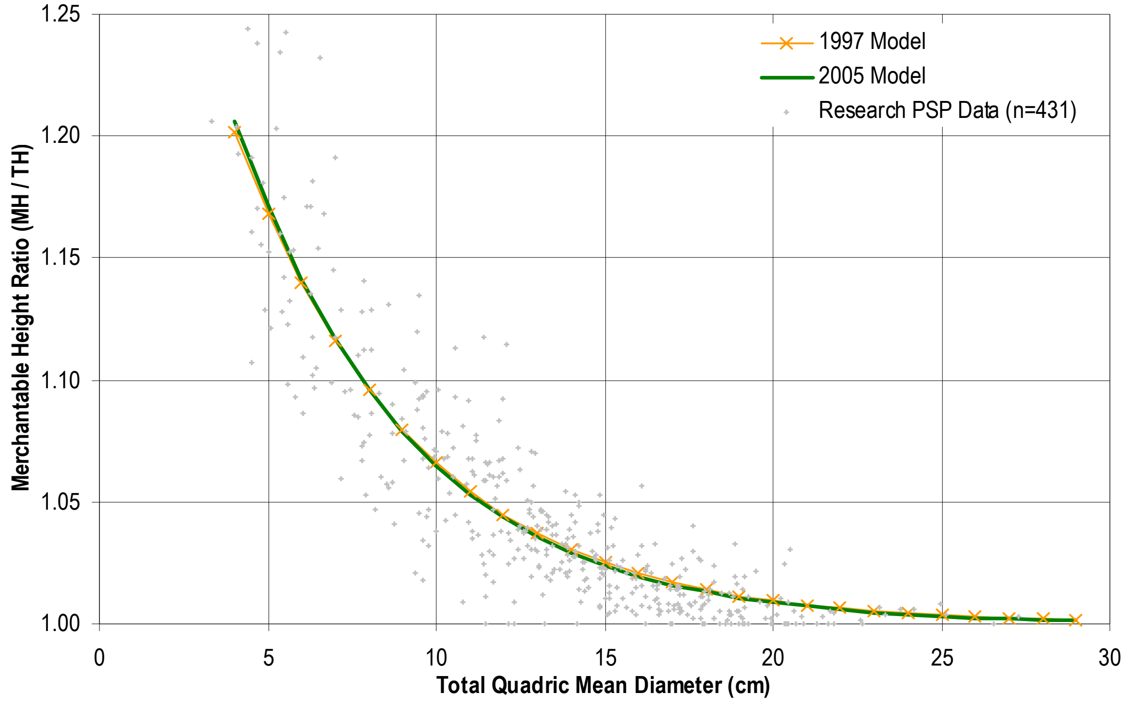


Figure 23. 2005 total to merchantable height ratio conversion function (F08) for natural stands.

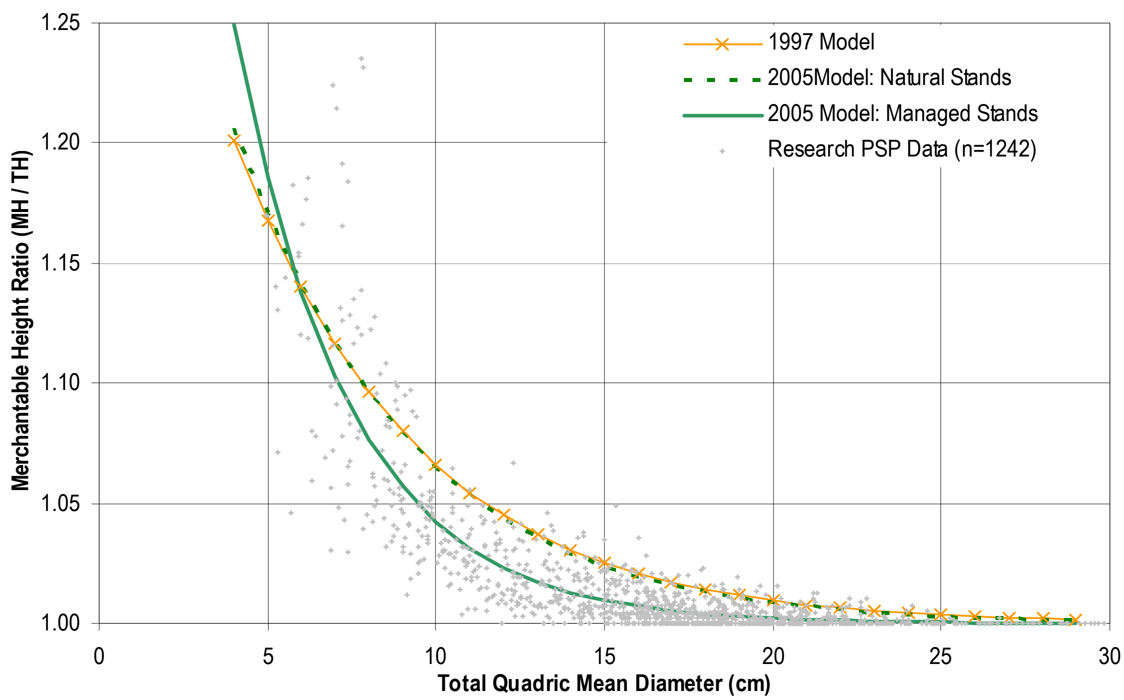


Figure 24. 2005 total to merchantable height ratio conversion function (F08t) for managed stands.

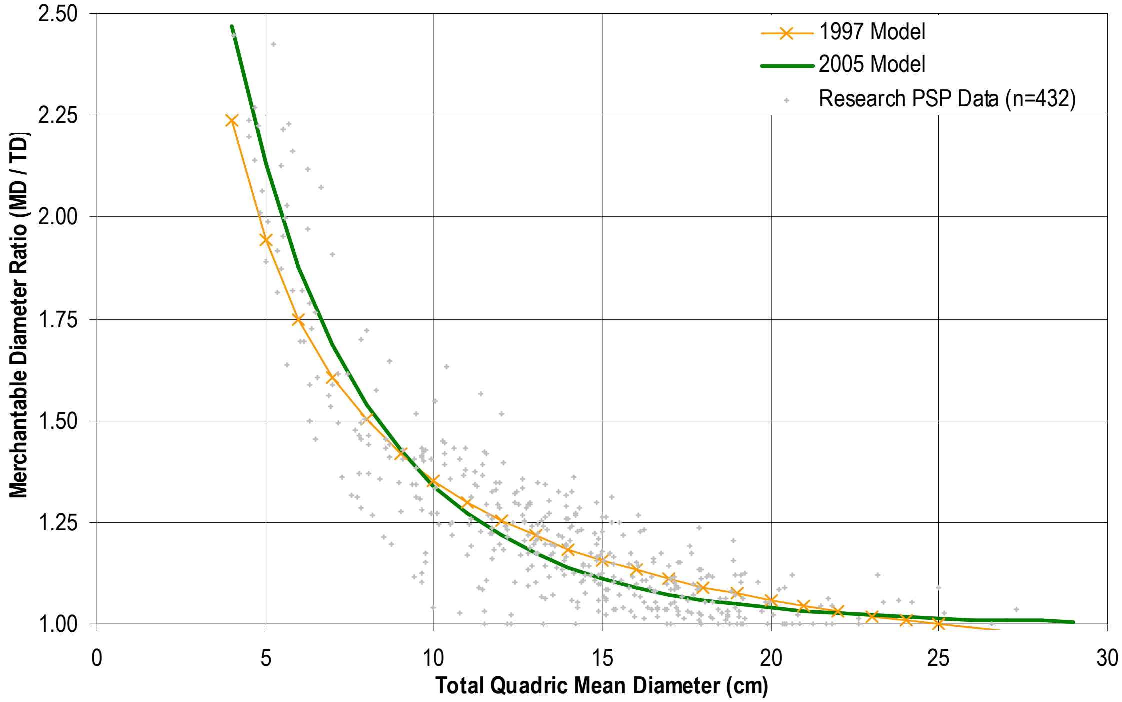


Figure 25. 2005 total to merchantable diameter ratio conversion function (F09) for natural stands.

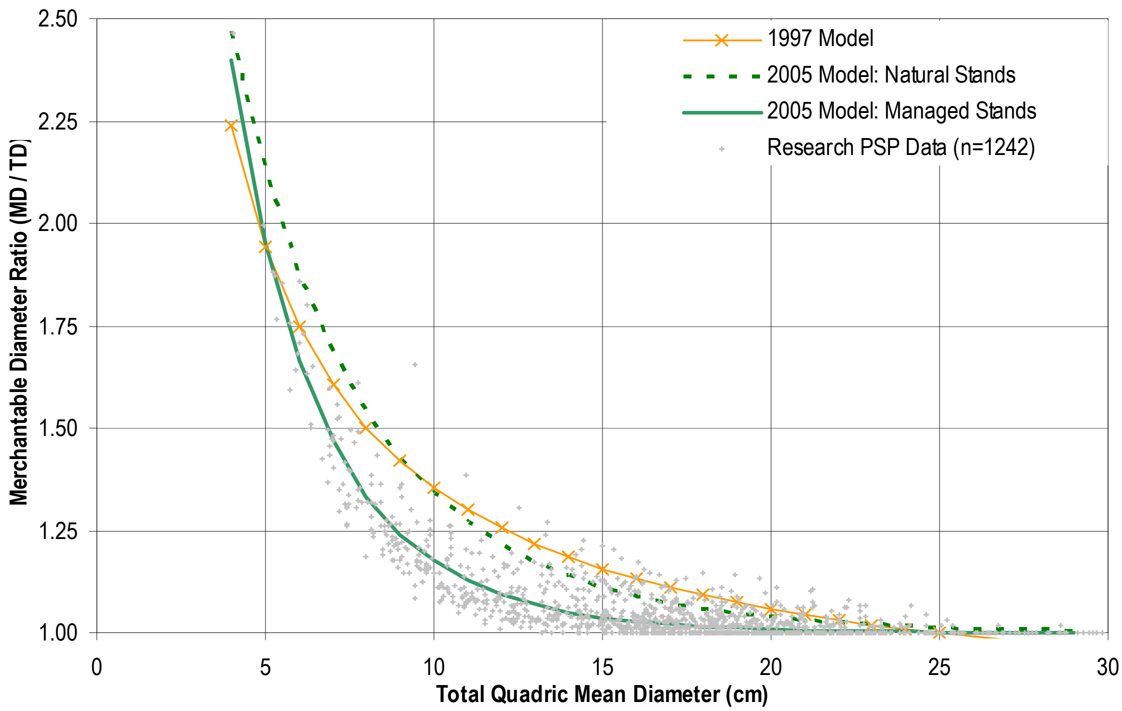


Figure 26. 2005 total to merchantable diameter ratio conversion function (F09t) for managed stands.

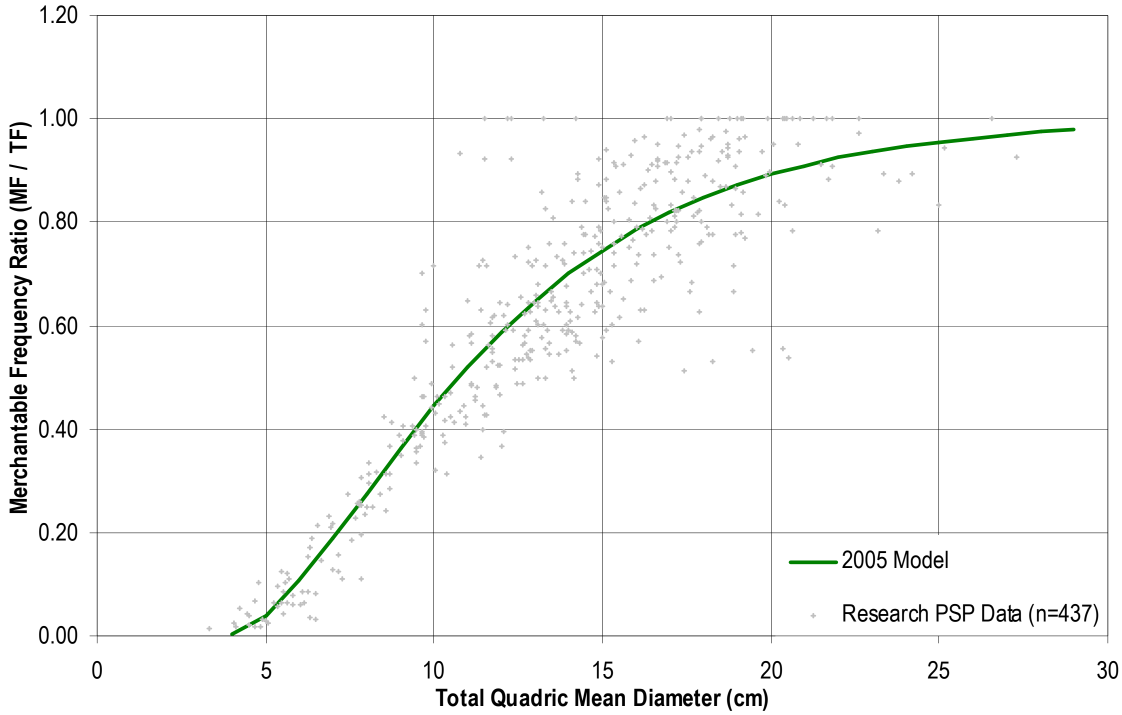


Figure 27. 2005 total to merchantable frequency ratio conversion function (F10) for natural stands.

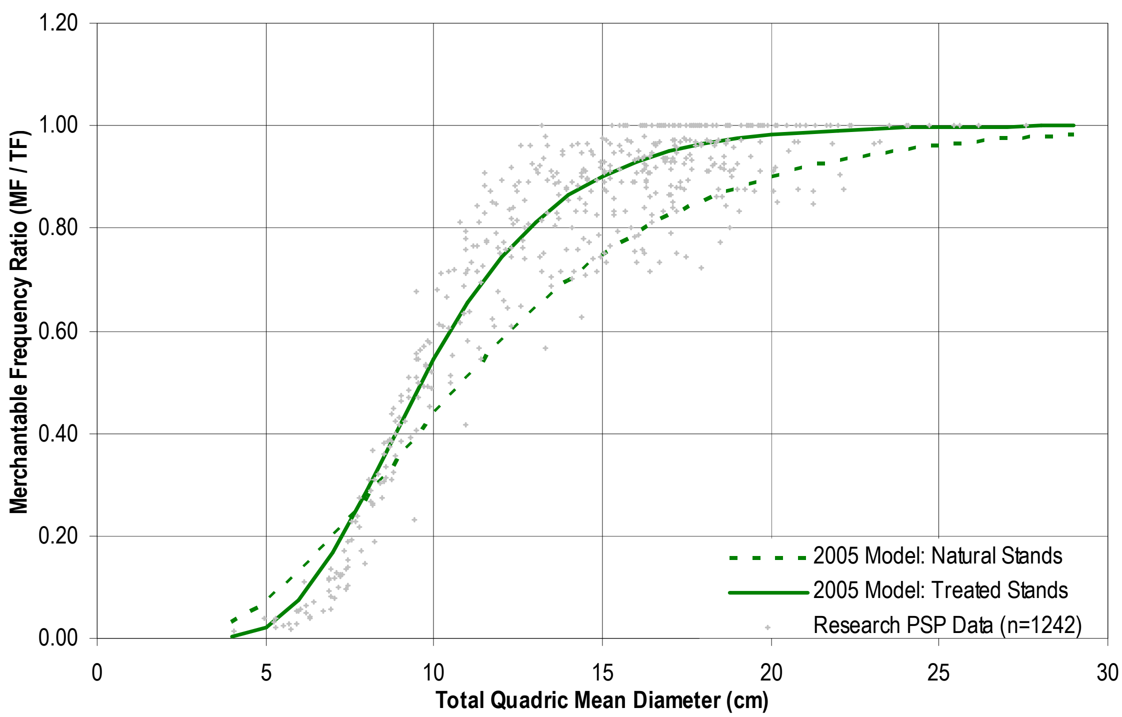


Figure 28. 2005 total to merchantable frequency ratio conversion function (F10t) for managed stands.

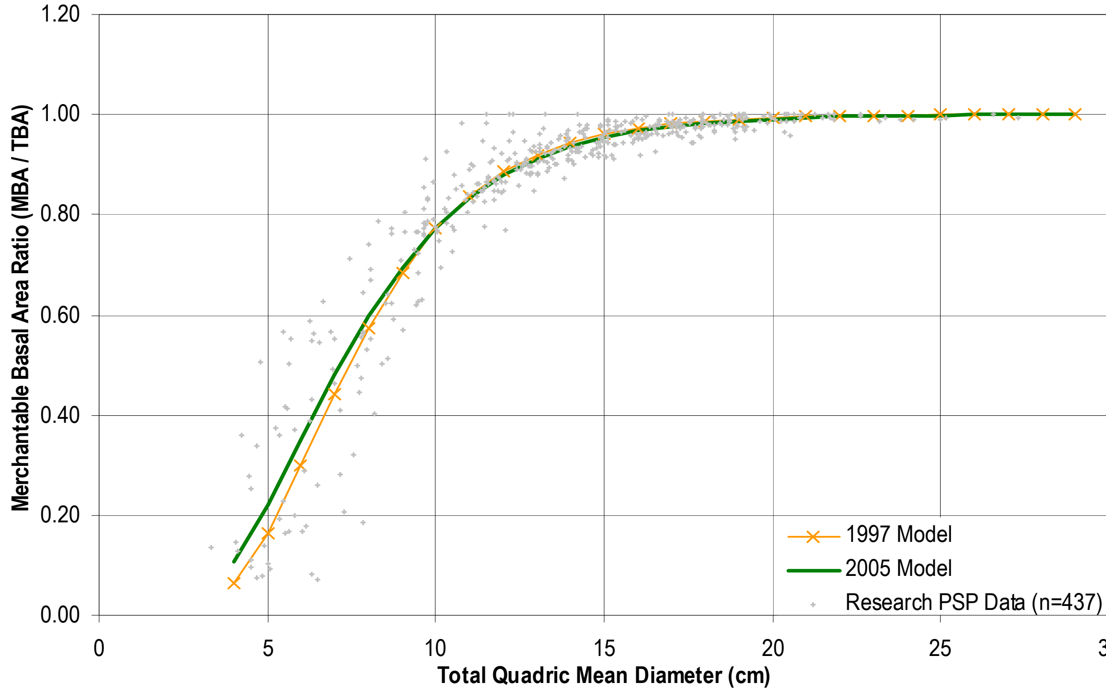


Figure 29. 2005 total to merchantable basal area ratio conversion function (F11) for natural stands.

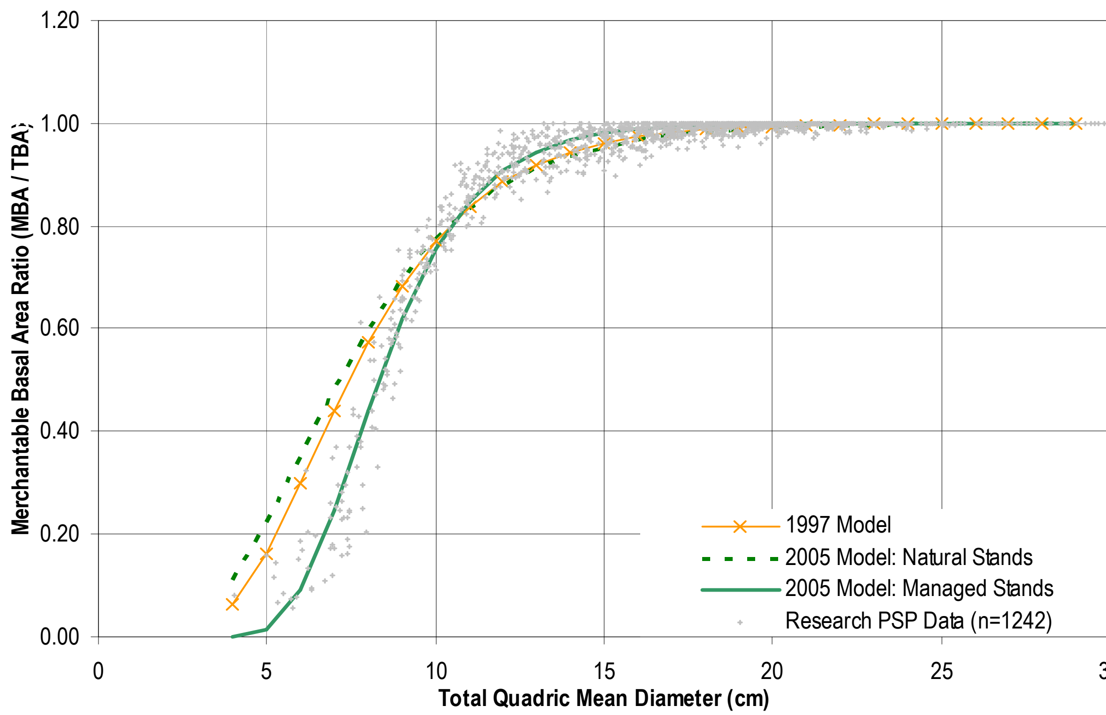


Figure 30. 2005 total to merchantable basal area ratio conversion function (F11t) for managed stands.

4.7 F14(t),15(t),16(t),17(t) – Sawlog Conversion Ratio Functions

In the 1997 model, the sawlog conversion function development was a mirror of the merchantable conversion process except that merchantable quadratic mean diameter (MD) was used as the independent variable rather than total quadratic mean diameter (TD). As described previously (Section 4.6), changes made to the merchantable conversion functions were replicated in the update of the sawlog conversion functions. However, more importantly, the 2005 update used a new sawlog specification. In the 1997 model, sawlog specifications were 15.24cm DBH and 10.16cm top. The 2005 update used a 25.4cm DBH and 20.32cm top. This change reduced the size of the database available since a large proportion of the plot data has no sawlog observations. Table 15 gives a summary of the updated sawlog conversion functions.

In comparison to the merchantable conversion functions, the r^2 values were far lower. This was a result of a smaller sample size, limited PSP observations in larger diameter (TD > 25cm) stands, and more within and between stand variations. In addition, the r^2 values for natural stand conversion functions were lower than those of managed stands (Table 15). The managed stand data had more observations that were better distributed across the range of diameter classes (Figure 31 to Figure 38).

Predicting the sawlog height conversion ratio was a challenge, as evident from Figure 31 and Figure 32 there is much variation associated with the 17-23cm merchantable diameter range. This large variation makes prediction difficult as evident by the low r^2 values; 0.162 and 0.246 for natural (F14) and managed (F14t) functions respectively (Table 15). The sawlog diameter conversion function (Figure 33 and Figure 34) fit the data better than the sawlog height conversions, showing higher r^2 values; 0.177 and 0.642 for natural (F15) and managed (F15t) functions respectively. The basal area conversion functions were a much better fit to the observed data (Figure 35 and Figure 36) having r^2 values of 0.671 and 0.768 for natural (F16) and managed (F16t) functions respectively. The 2005 natural unmanaged sawlog frequency conversion function was created using a model similar to the other ratio functions. The function (F17) fit the data well with an r^2 value of 0.786 (Figure 37). The associated managed stand function (F17t) also fit the data well (r^2 value of 0.895) and, in comparison to the unmanaged function, it shows an accelerated transition, similar to observations in other managed stand conversion functions.

Testing of the four sets of conversion functions led to the selection of height, diameter and frequency to perform the merchantable to sawlog conversion. The model uses sawlog diameter and frequency predictions to calculate sawlog basal area. The sawlog basal area conversion functions (F16, F16t) remain in the model and can be enabled for future development or testing as needed.

Table 15. Summary of sawlog conversion functions (F14(t),15(t),16(t),17(t)).

Function	Attribute	2005 Model
F14		
	Sample Size	173
	Model Form	BHrat = $(1+e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.0883
	ß1	0.5563
	r^2	0.162
F14t		
	Sample Size	722
	Model Form	BHrat = $(1+e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.1163
	ß1	0.7595
	r^2	0.246
F15		
	Sample Size	177
	Model Form	BDrat = $(1+e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.0682
	ß1	1.8245
	r^2	0.177
F15t		
	Sample Size	722
	Model Form	BDrat = $(1+e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.1104
	ß1	3.5178
	r^2	0.642
F16		
	Sample Size	177
	Model Form	BBArat = $(1-e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.1463
	ß1	21.3988
	r^2	0.671
F16t		
	Sample Size	722
	Model Form	BBArat = $(1-e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.1769
	ß1	44.4532
	r^2	0.768
F17		
	Sample Size	177
	Model Form	BFrat = $(1-e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.1128
	ß1	18.0107
	r^2	0.786
F17t		
	Sample Size	722
	Model Form	BFrat = $(1-e^{ß0*MD})^{ß1}$
	Parameters	
	ß0	-0.1556
	ß1	45.8779
	r^2	0.895

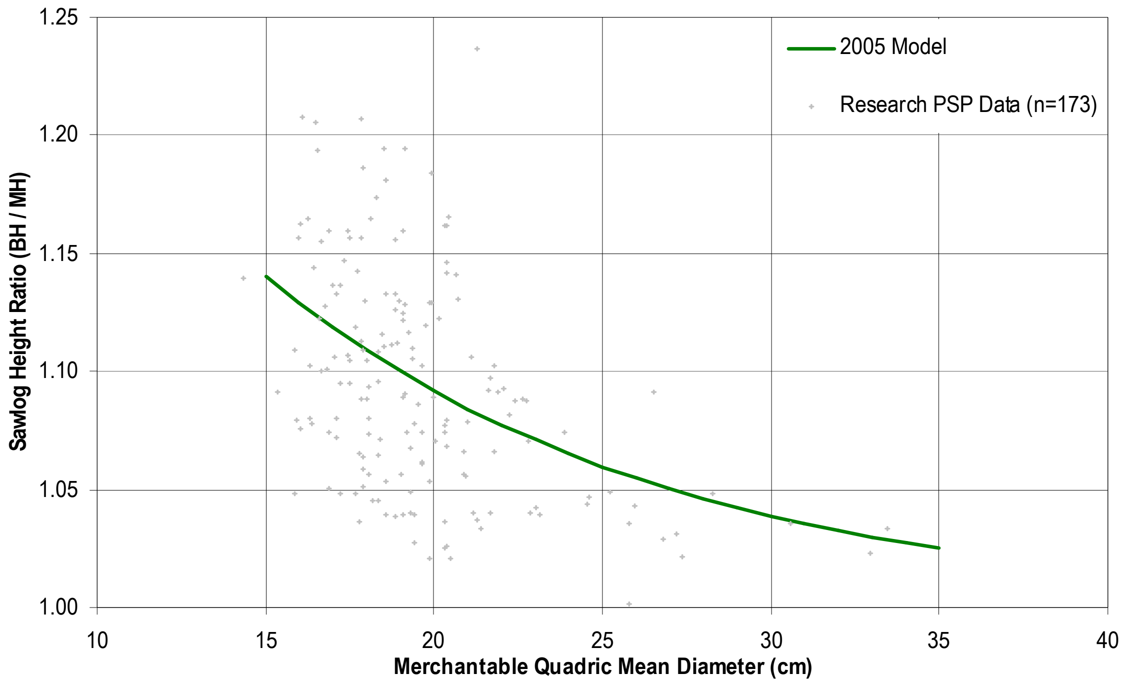


Figure 31. 2005 merchantable to sawlog height ratio conversion function (F14) for natural stands.

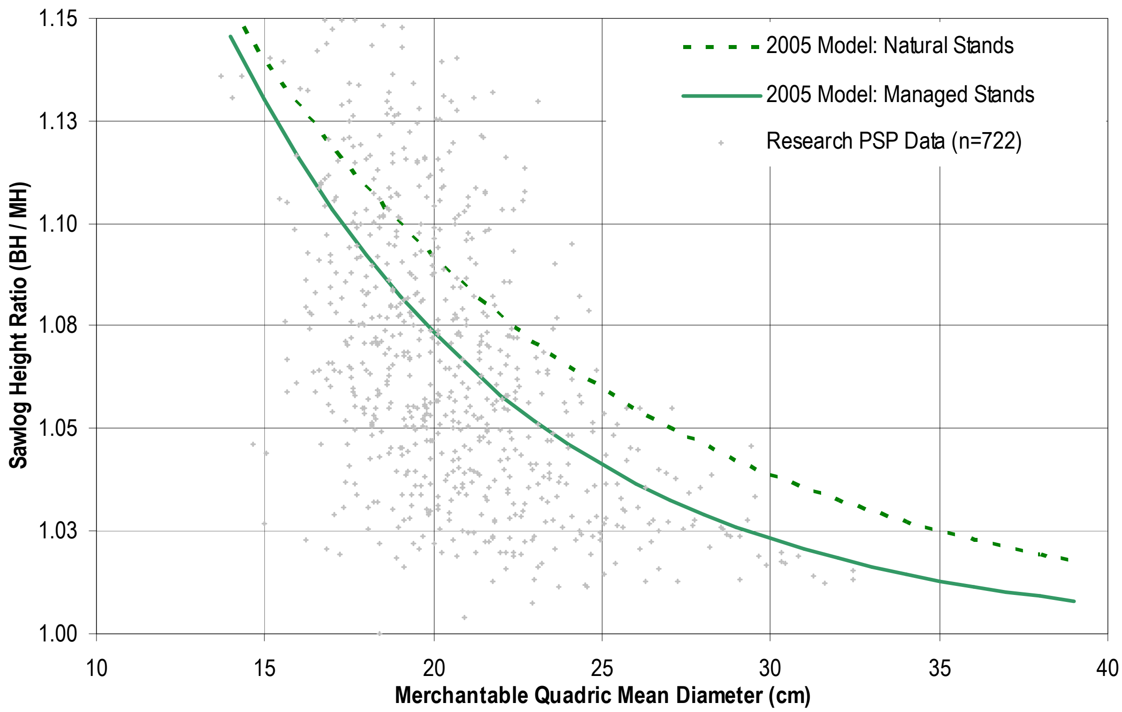


Figure 32. 2005 merchantable to sawlog height ratio conversion function (F14t) for managed stands.

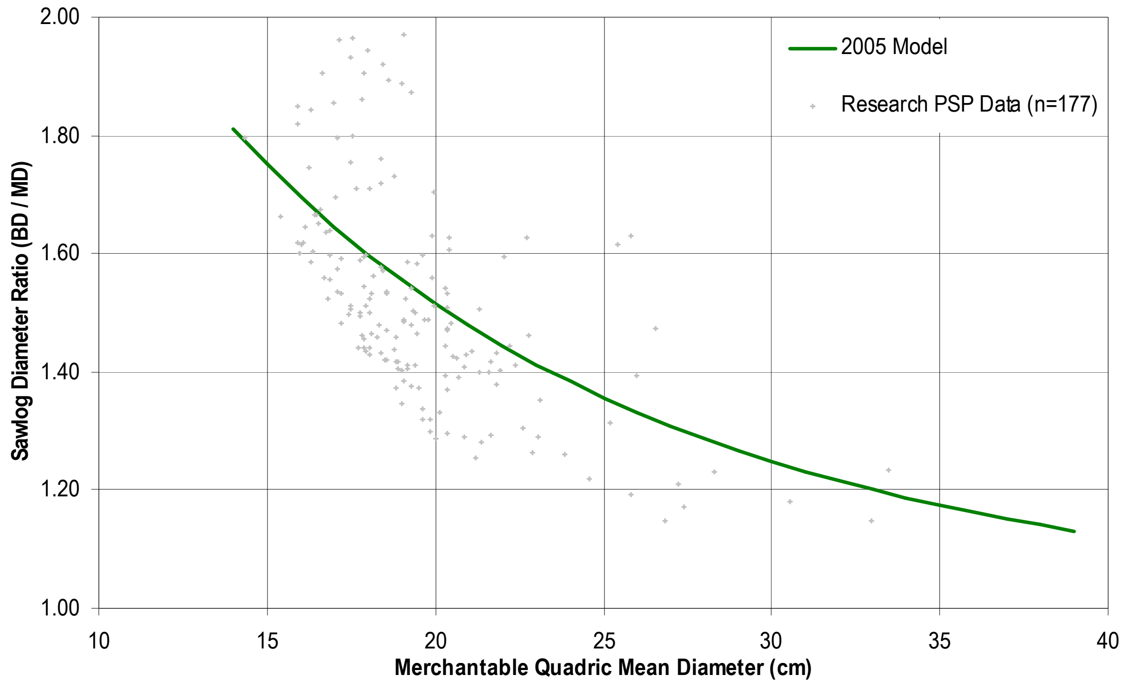


Figure 33. 2005 merchantable to sawlog diameter ratio conversion function (F15) for natural stands.

Figure 34. 2005 merchantable to sawlog diameter ratio conversion function (F15t) for managed stands.

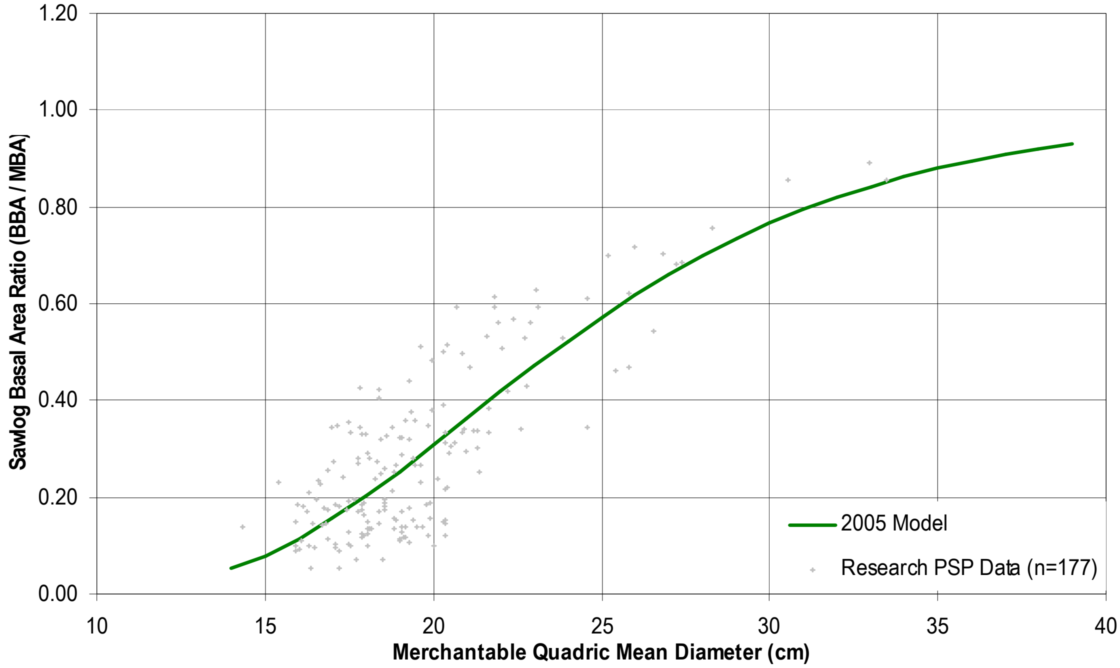


Figure 35. 2005 merchantable to sawlog basal area ratio conversion function (F16) for natural stands.

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Figure 36. 2005 merchantable to sawlog basal area ratio conversion function (F16t) for managed stands.

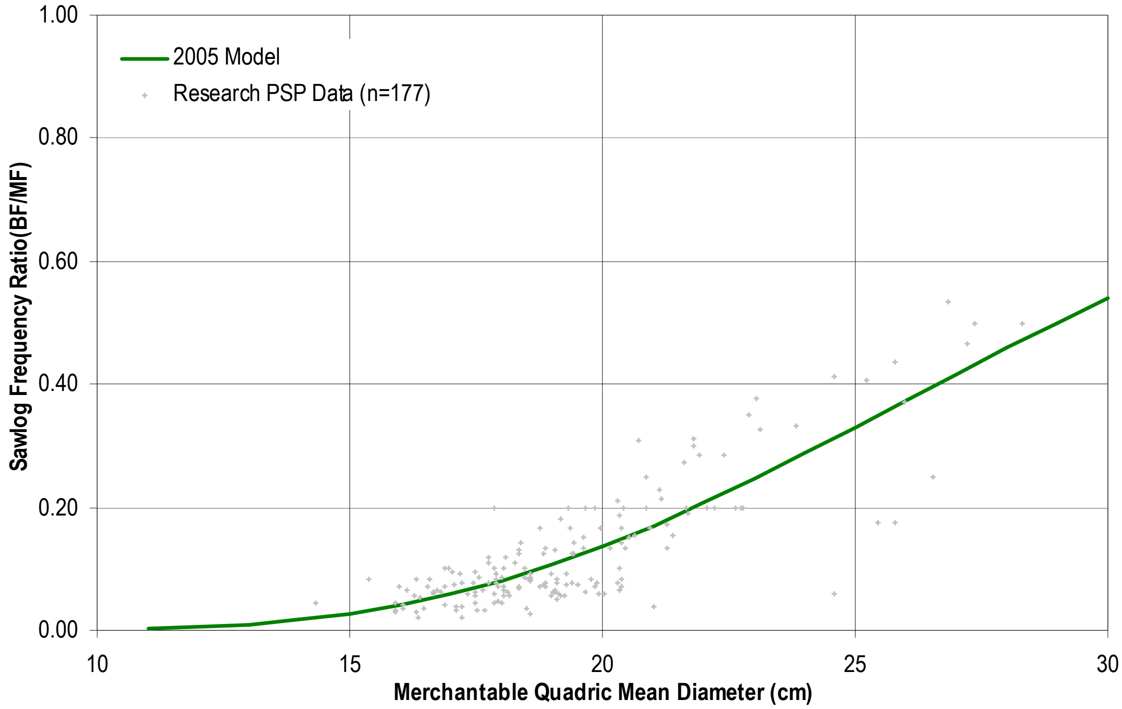

Figure 37. 2005 merchantable to sawlog frequency ratio conversion function (F17) for natural stands.

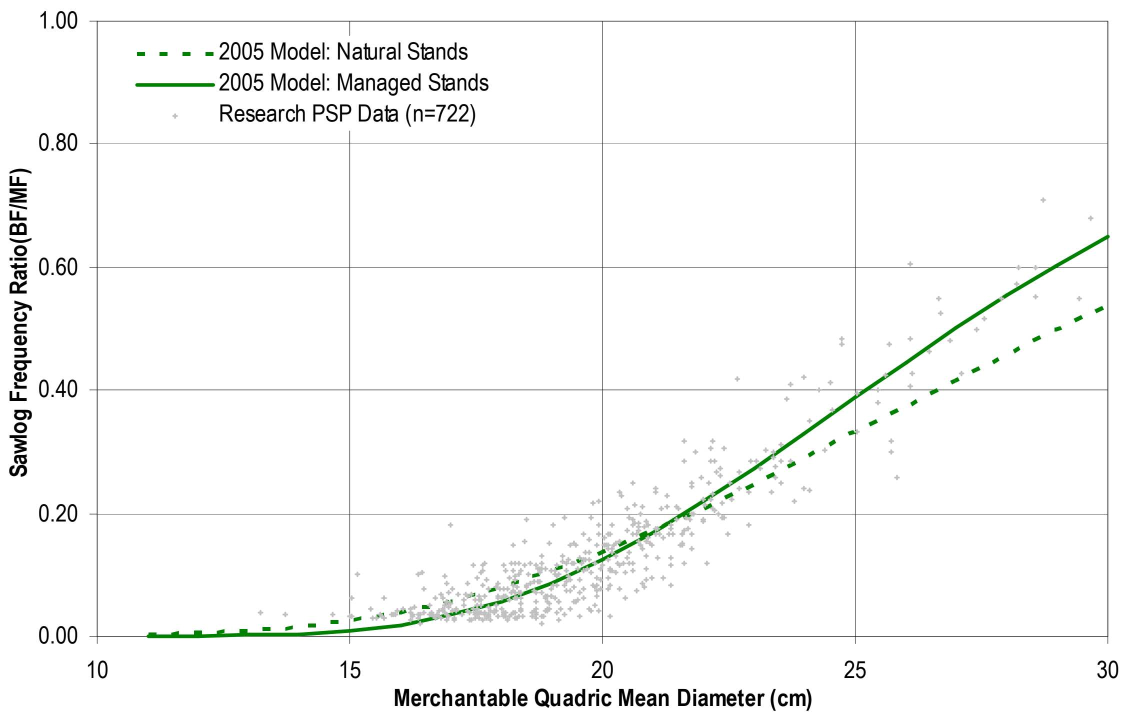

Figure 38. 2005 merchantable to sawlog frequency ratio conversion function (F17t) for managed stands.

5 Model Evaluation

The evaluation of the model performance was carried out using two approaches. First, the natural unmanaged growth functions (F03, F04, and F05) were compared to observations in the Inventory PSP database. The second part compared age-based model outputs to observations in the Research PSP database.

5.1 Comparison of Natural Unmanaged Growth Functions (F03, F04, F05) to Inventory PSP Data.

The Inventory PSP database, as described earlier, was not suited for model development yet was used to gauge the validity of the main natural unmanaged growth functions developed (F03, F04 and F05). This was accomplished by plotting the new functions with the Inventory PSP observations. Average Height as ƒ(Dominant Height), Total Diameter as ƒ(Average Height, Site Index) and Total Density as ƒ(Total Diameter, Species Group) were the three functions addressed.

5.1.1 F03 – Average Height as ƒ(Dominant Height)

Figure 39 shows the 2005 average height function (F03) plotted with the Inventory PSP observations. The majority of the 2,351 observations fall below the function reflecting the variability in the Inventory PSP database. In theory, where all stems are of equal height, the average height (AH) to dominant height (DH) ratio is a 1:1 relationship. The further the stand is from this theoretical condition, the further AH decreases in relation to DH. The fact that the vast majority of the Inventory observation fall below the F03 function lends confidence to the assumption that the Research data are capturing the fully stocked (i.e. 'normal') condition.

A few of the observations fell above the function (Figure 39). This happened when AH was greater than DH, and was associated with plots having few trees (<6) and large height variations. It was an artifact of differences in calculation methods. The AH calculation was weighted by basal area so 1 or 2 small trees would not affect the average height yet dominant height was simply the arithmetic average; therefore shorter trees had a greater influence on the mean height.

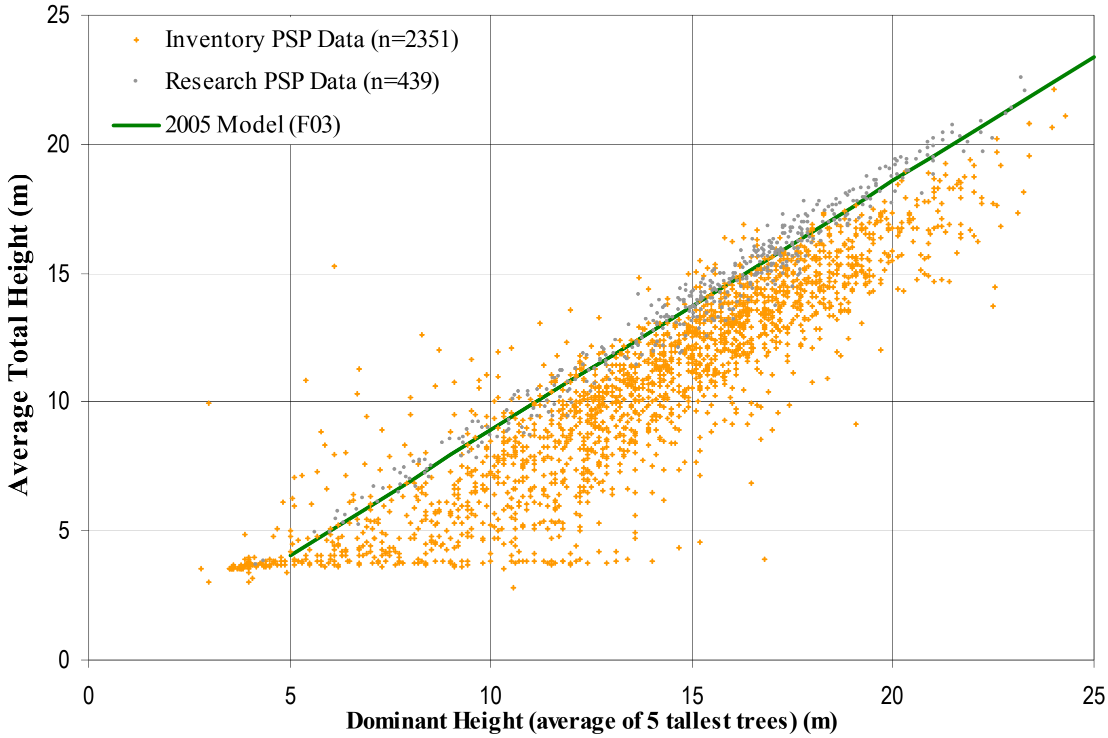

Figure 39. 2005 Average height function (F03) plotted with Inventory and Research PSP data.

5.1.2 F04 – Total Diameter as ƒ(Average Height, Site Index)

The 2005 total diameter (TD) function (F04) is based on two independent variables, average height (AH) and site index (SIB). In order to plot the function with the Inventory PSP data they were stratified into five site index classes. Figure 40 to Figure 44 present the plots for each site index class. The majority of Inventory PSP observations fell above the total diameter function (i.e. on average, total diameter was larger for any given height). The fact that the data borders the function suggested that the function has adequately captured the fully stocked condition. A major change to the 2005 model was the addition of the site index variable. The stratified inventory PSP data additionally shows indications that site index is affecting the height-diameter relationship in unmanaged stands.

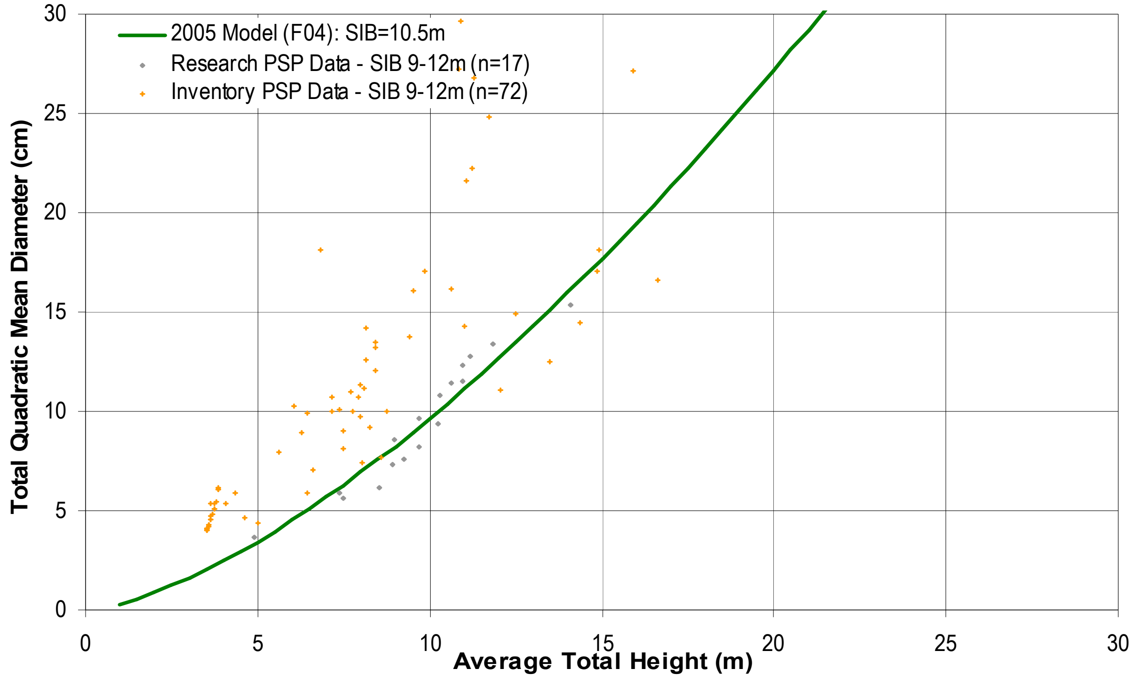

Figure 40. 2005 total diameter function (F04) plotted with Inventory and Research PSP data for the 9-12m site index class.

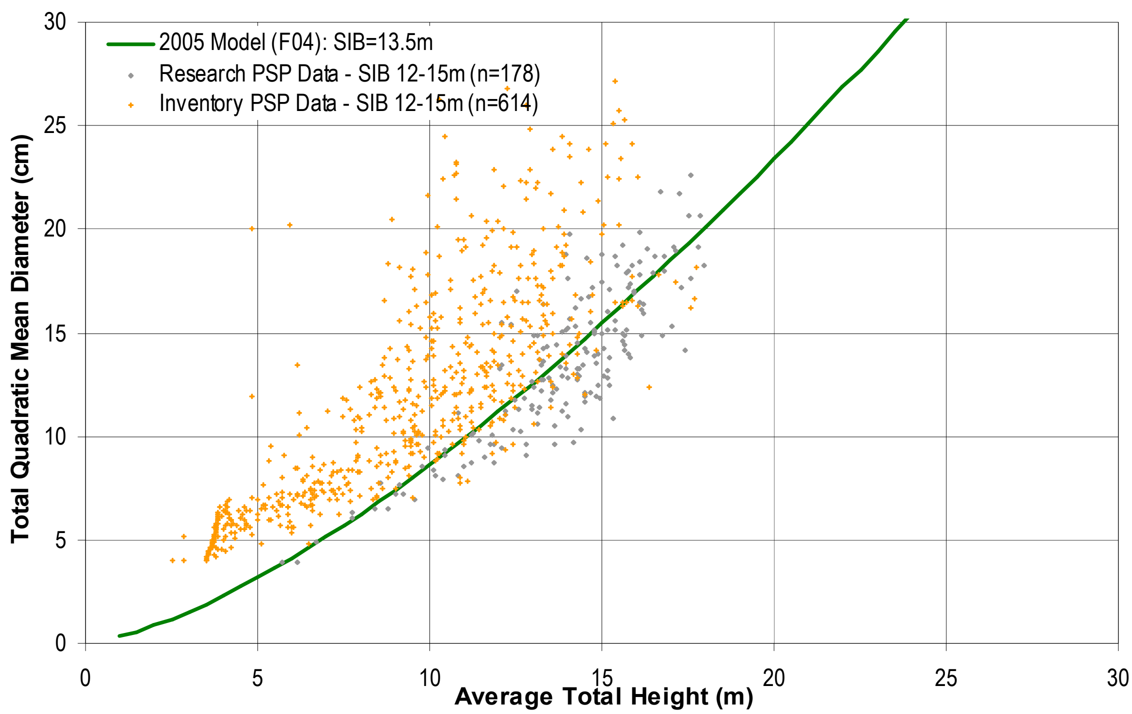

Figure 41. 2005 total diameter function (F04) plotted with Inventory and Research PSP data for the 12-15m site index class.

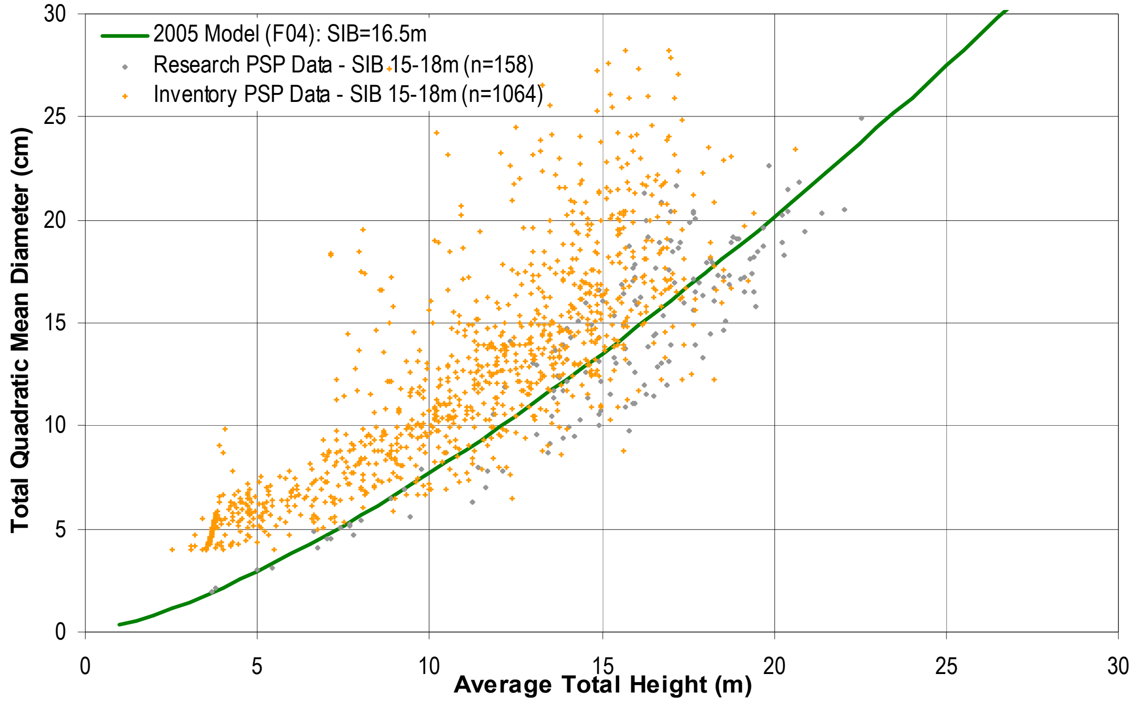

Figure 42. 2005 total diameter function (F04) plotted with Inventory and Research PSP data for the 15-18m site index class.

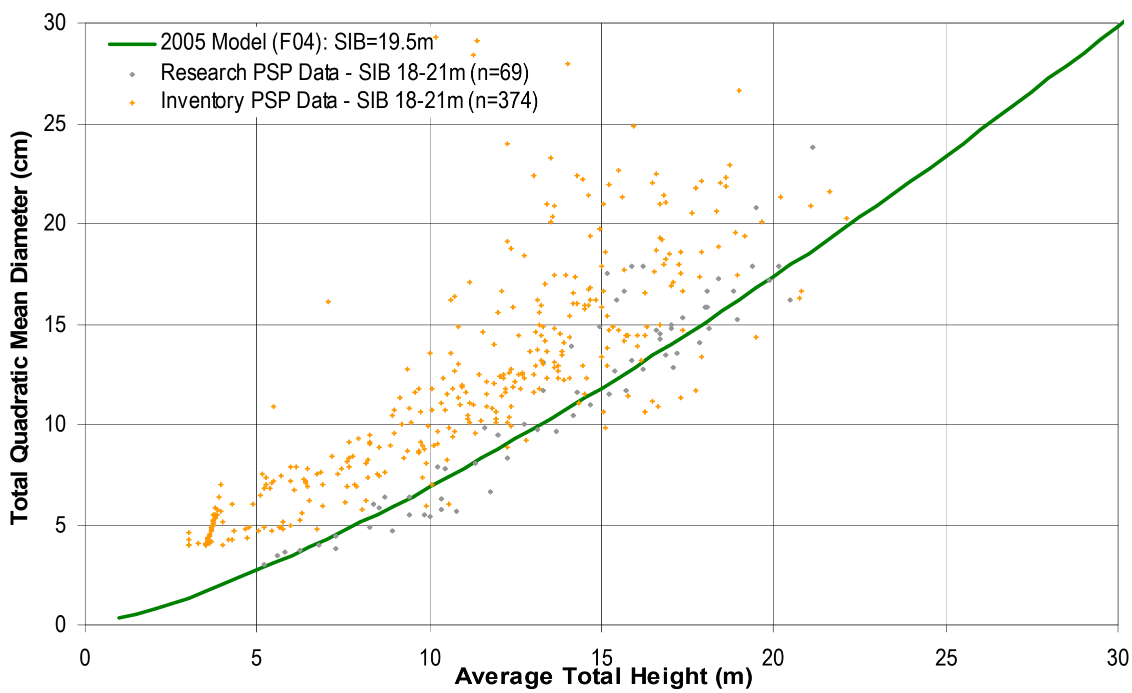

Figure 43. 2005 total diameter function (F04) plotted with Inventory and Research PSP data for the 18-21m site index class.

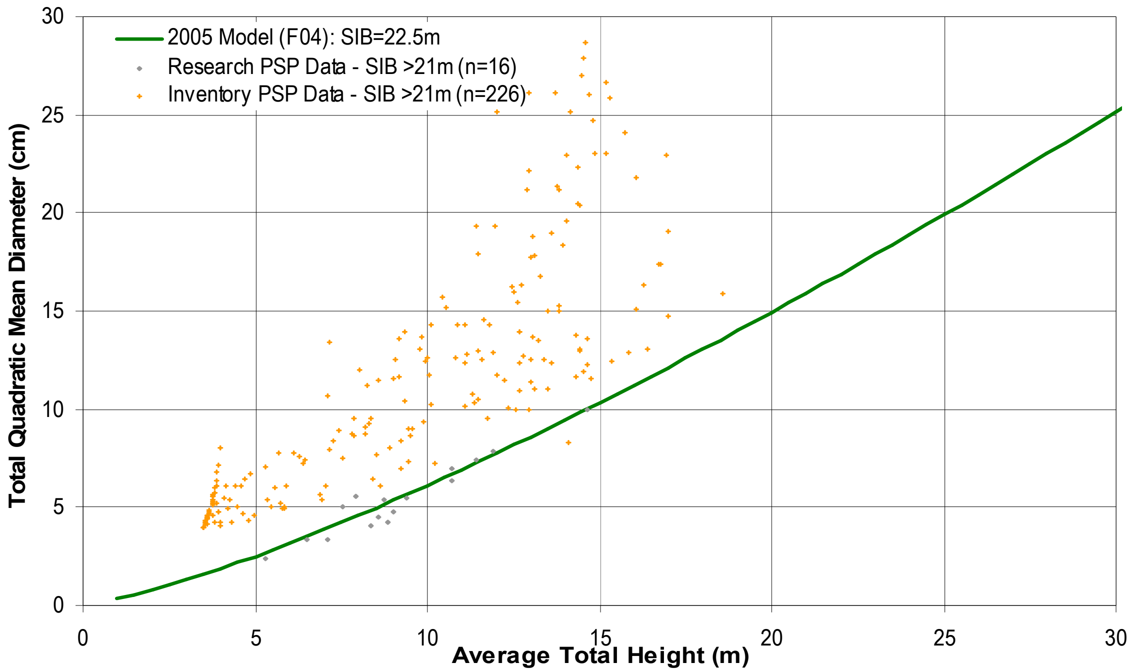

Figure 44. 2005 total diameter function (F04) plotted with Inventory and Research PSP data for the 21m+ site index class.

5.1.3 F05 – Total Frequency as ƒ(Total Diameter, Species Group)

The 2005 total frequency (TF) function takes total diameter (TD) and species group as independent variables. The model evolved from the 1997 function that was simply a function of TD. To view the predictions with observed Inventory PSP data, plots were created for each of the three species groups (Figure 45 to Figure 47). As a general observation, the observed inventory data fell below the total density predictions for each species group. This was as expected as the Inventory PSPs are a random sample reflective of the range of stocking levels present across the forest. This observation supports the major assumption that the sample is representative of fully-stocked stands.

The Inventory PSP observations for the tolerant group (Figure 45) showed the tightest grouping of the three species groups. The predicted density line was tight to the upper limit of the observations. There were a few observations that exceeded the density predictions yet they were still within the cloud of Research PSP observations used to derive the function. The 51 Aspen observations (Figure 46) represented only 2% of the entire Inventory PSP database suggesting stands dominated by Aspen are not a prevalent component of the hardwood forests of the province. Even with the small Aspen sample, the cloud of points fell below the predictions as expected. The cloud of Inventory PSP observations for the intolerant species group (Figure 47) mostly fell below the predicted density. The cloud does however go above the predicted line far more than observed with other species groups. This is especially noticeable in the range of diameters between 10-18cm. A closer look at the data indicated a large proportion of the Intolerant

Inventory PSP observations were red maple with relatively high amounts of softwood (as Inventory PSP hardwood plots could have up to 25% softwood basal area).

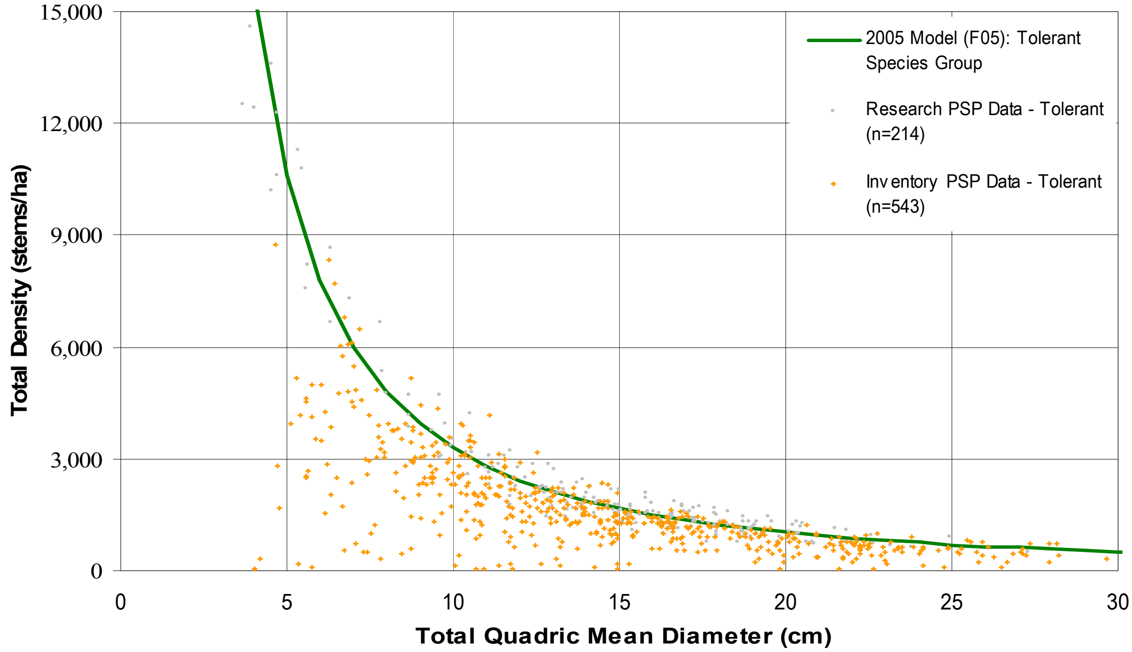

Figure 45. 2005 total density function (F05) plotted with Inventory and Research PSP data for the tolerant species group.

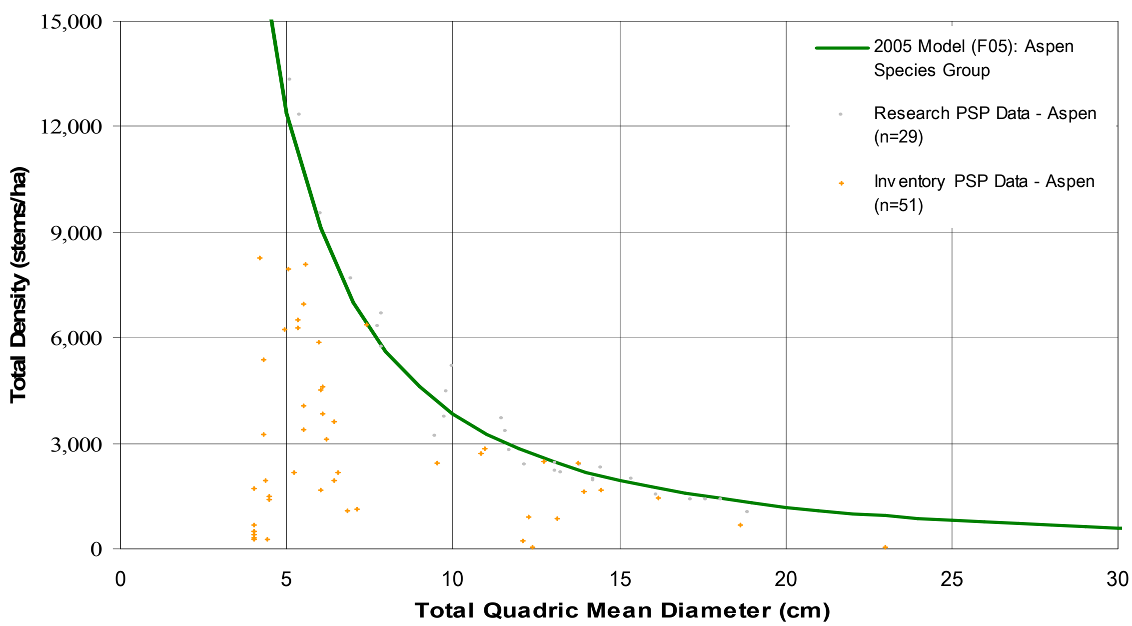

Figure 46. 2005 total density function (F05) plotted with Inventory and Research PSP data for the Aspen species group.

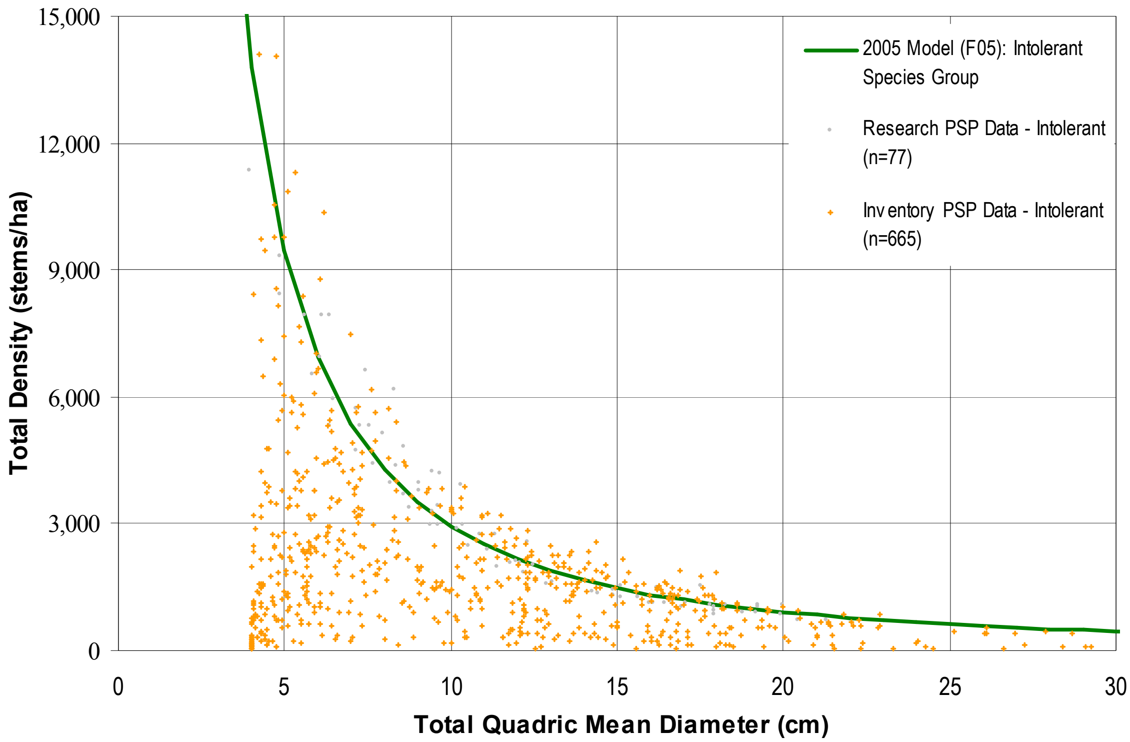

Figure 47. 2005 total density function (F05) plotted with Inventory and Research PSP data for the intolerant species group.

5.2 Evaluation of stand level estimates

The same data from the Research PSP database were used for both the evaluation procedure and model development, albeit in different ways. The model development process focused on functional relationships between specific stand characteristics and, therefore, age-based model predictions are not derived from age-based observations. This made comparing observed age-based characteristics (height, diameter, density, basal area and volume) to model predictions a meaningful measure of model performance.

The evaluation procedure looked at five stand characteristics (height, diameter, density, basal area and volume) by three product classes (total, merchantable and sawlog). The evaluation was additionally stratified by the three species groups (tolerant, intolerant and Aspen). The evaluation statistics used are summarized in Table 16 and the results are presented in Figure 48 and Table 17 to Table 19. The calculation of residual statistics was based on procedures outlined in a similar growth and yield report by Knoebel, Burkhart and Beck (1986).

Table 16. Summary of model evaluation summary statistics.

Statistic	Description	Formula
Absolute Minimum	Absolute minimum of residuals calculated as observed minus predicted.	
Absolute Maximum	Absolute maximum residual value calculated as observed minus predicted.	
Mean	Mean of all residual values calculated as observed minus predicted.	$M = \sum_{i=1}^{n} r_i \Big/ n$
Absolute Mean	Mean of absolute residual values calculated as observed minus predicted.	$M_a = \sum_{i=1}^{n} ABS(r_i) \Big/ n$
Standard Deviation	Mean of all residual values calculated as observed minus predicted.	$SD = \sqrt{\dfrac{\sum_{i=1}^{n} r_i^2 - \left(\sum_{i=1}^{n} r_i\right)^2 \Big/ n}{n-1}}$
R^2	Coefficient of determination.	$r^2 = 1 - \dfrac{\sum_{i=1}^{n} r_i^2}{\sum_{i=1}^{n} (\overline{y} - y_i)^2}$

Formula Variables:
- M = Mean
- Ma = Absolute Mean
- SD = Standard Deviation
- r_i = i^{th} Residual Value (Observed – Predicted)
- n = Number of Observations
- ABS = Absolute Value of Variable
- y_i = i^{th} Observed Value
- y-bar = Mean of Observed Values

Generally, the model predictions for total stand characteristics were more accurate than the merchantable predictions which were, in turn, more accurate than sawlog predictions as evident by the observed R^2 scores (Figure 48 and Table 17 to Table 19). This trend was consistent across most stand characteristics and species groups. For the intolerant and Aspen sawlog predictions, the model was less accurate, showing far lower R^2 scores across all stand characteristics. This was related to limitations of underlying data where Aspen represented only a small portion of the data and both the Aspen and intolerant species groups had limited representation in larger diameter stands where one would expect sawlogs.

Comparing predictions across species groups showed similar R^2 scores across most stand characteristics and product classes.

Predictions for total dominant height and total average height described 97.1 - 99.6 percent of the observed variation. This lends confidence to the site index curves (NSDNR, 1987) that control height growth in the model. Total diameter predictions generated R^2 scores of 0.778 - 0.879, though not as high as height predictions they also support changes made to the diameter growth functions in the model (F04 or F18 depending on whether the stand is unmanaged or managed). Total density predictions showed higher R^2 scores (0.892 - 0.963) lending support to the new species based density function (F05). The total basal area R^2 scores (ranged from 0.902 - 0.922) were higher than diameter and in most cases slightly less than those observed for density. The volume estimates were consistently better than basal area likely the result of the more accurate height characteristic being used in the volume determination.

Overall, the model performed well for all stand characteristics and species groups. The only concern was in relation to sawlog estimates. The sawlog prediction performance was less reliable, in particular for the Aspen and intolerant species groups. The tolerant sawlog predictions were relatively more accurate especially for basal area and volume characteristics.

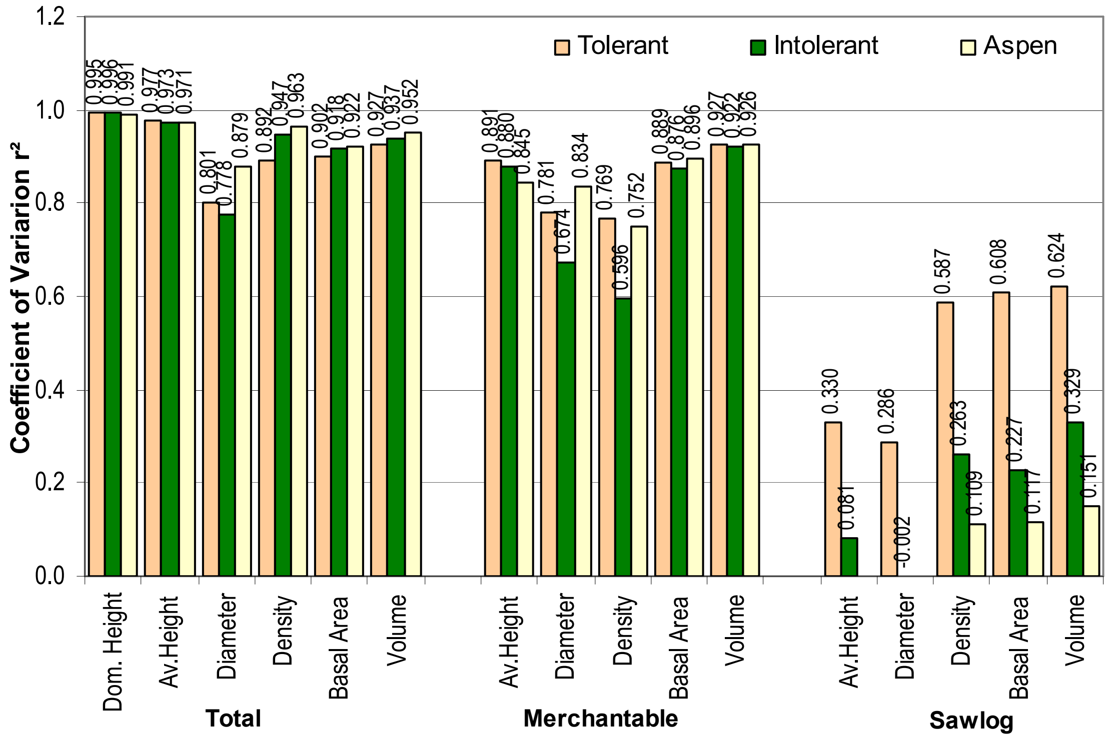

Figure 48. Summary of R^2 values for stand attributes by product class and species group.

Table 17. Statistics generated from model evaluation of the tolerant species group.

Product Class	Stand Attribute	Units	n	Absolute Min	Absolute Max	Mean	Absolute Mean	Standard Deviation	R^2
Total									
	Dom. Height	m	728	0.0	0.9	0.0	0.2	0.2	0.995
	Av. Height	m	728	0.0	2.3	0.1	0.4	0.3	0.977
	Diameter	cm	728	0.0	12.8	0.8	1.8	1.5	0.801
	Density	stems/ha	728	0.1	6279.6	56.4	264.6	584.1	0.892
	Basal Area	m²/ha	728	0.0	19.6	0.7	1.6	1.9	0.902
	Volume	m³/ha	728	0.0	127.7	7.8	12.3	13.9	0.927
Merch.									
	Av. Height	m	728	0.0	9.8	-0.1	0.6	1.1	0.891
	Diameter	cm	728	0.0	12.3	0.9	1.8	1.7	0.781
	Density	stems/ha	728	0.0	967.0	-50.2	136.9	129.0	0.769
	Basal Area	m²/ha	728	0.0	0.0	0.5	1.9	2.0	0.889
	Volume	m³/ha	728	0.0	101.7	4.1	11.9	12.2	0.927
Sawlog									
	Av. Height	m	728	0.0	20.7	-2.8	3.5	6.5	0.330
	Diameter	cm	728	0.0	32.2	-2.7	6.2	10.3	0.286
	Density	stems/ha	728	0.0	194.6	12.4	35.7	35.2	0.587
	Basal Area	m²/ha	728	0.0	19.4	1.2	2.7	2.7	0.608
	Volume	m³/ha	728	0.0	154.1	8.5	15.8	18.1	0.624

Table 18. Statistics generated from model evaluation of the intolerant species group.

Product Class	Stand Attribute	Units	n	Absolute Min	Absolute Max	Mean	Absolute Mean	Standard Deviation	R^2
Total									
	Dom. Height		311	0.0	1.8	-0.1	0.2	0.1	0.996
	Av. Height	m	311	0.0	1.8	-0.1	0.4	0.3	0.973
	Diameter	cm	311	0.0	6.2	-0.6	1.7	1.4	0.778
	Density	stems/ha	311	0.0	2182.6	105.6	250.4	327.5	0.947
	Basal Area	m^2/ha	311	0.0	7.9	0.6	1.2	1.2	0.918
	Volume	m^3/ha	311	0.0	41.7	1.8	8.2	7.9	0.937
Merch.									
	Av. Height	m	311	0.0	9.0	-0.4	0.6	1.1	0.880
	Diameter	cm	311	0.0	9.9	-0.9	1.8	1.7	0.674
	Density	stems/ha	311	0.0	837.1	70.9	199.1	163.3	0.596
	Basal Area	m^2/ha	311	0.0	0.0	0.3	1.8	1.8	0.876
	Volume	m^3/ha	311	0.0	52.4	-1.8	9.5	8.8	0.922
Sawlog									
	Av. Height	m	311	0.0	19.3	-5.2	5.4	7.7	0.081
	Diameter	cm	311	0.0	29.7	-8.4	8.9	12.6	-0.002
	Density	stems/ha	311	0.0	158.2	-15.3	22.7	26.3	0.263
	Basal Area	m^2/ha	311	0.0	8.9	-1.0	1.5	1.8	0.227
	Volume	m^3/ha	311	0.0	61.2	-4.2	7.3	9.0	0.329

Table 19. Statistics generated from model evaluation of the Aspen species group.

Product Class	Stand Attribute	Units	n	Absolute Min	Absolute Max	Mean	Absolute Mean	Standard Deviation	R^2
Total									
	Dom. Height		125	0.0	1.3	-0.2	0.3	0.2	0.991
	Av. Height	m	125	0.0	2.0	-0.2	0.5	0.4	0.971
	Diameter	cm	125	0.0	6.2	-0.1	1.3	1.3	0.879
	Density	stems/ha	125	0.4	4907.2	-21.9	199.7	484.4	0.963
	Basal Area	m^2/ha	125	0.0	8.2	-1.4	2.1	2.0	0.922
	Volume	m^3/ha	125	0.0	45.6	-6.2	12.5	11.3	0.952
Merch.									
	Av. Height	m	125	0.0	9.1	-0.6	0.9	1.7	0.845
	Diameter	cm	125	0.0	9.2	-0.5	1.7	1.6	0.834
	Density	stems/ha	125	0.0	1664.5	1.7	227.3	296.3	0.752
	Basal Area	m^2/ha	125	0.0	0.0	-1.4	2.6	2.5	0.896
	Volume	m^3/ha	125	0.0	57.5	-11.1	15.4	13.1	0.926
Sawlog									
	Av. Height	m	125	0.0	19.3	-3.6	5.1	7.5	-0.212
	Diameter	cm	125	0.0	33.8	-5.4	9.2	12.8	-0.269
	Density	stems/ha	125	0.0	223.5	-7.5	25.3	37.9	0.109
	Basal Area	m^2/ha	125	0.0	14.9	-0.4	1.8	2.6	0.117
	Volume	m^3/ha	125	0.0	85.2	-2.4	9.6	15.1	0.151

5.2.1 Comparison with 1997 Model

As a final step in the evaluation, the same residual statistics (Table 16) used in evaluation of the 2005 model were compiled for the 1997 model. The only difference was the sawlog residual statistics could not be compiled for comparison as the 2005 model used a different sawlog specification. Table 20 summarizes the residual statistics for the 1997 model and Figure 49 to Figure 51 compare the 1997 and 2005 R^2 statistic for each of the three species groups.

The comparison showed that the 2005 model performed better than the 1997 model which was evident by the higher R^2 scores and lower standard deviations of the residual statistics. With the exception of some small variations, all R^2 scores increased in the 2005 model, some by as much as 41%.

Residual statistics for total dominant height and total average height between the 1997 and 2005 model were similar across all species groups. This was expected as the 2005 update only made minor changes to the total average height function (F03 and F03t). Residual statistics for the total diameter, total density, total basal area and total volume showed noticeable improvements in performance as a result of the 2005 update. This provides support for the new site index based diameter function (F04), the new species based managed stand diameter growth function (F18) and the new species based density function (F05).

In comparing the performance by product class it was evident the R^2 values increased by a larger percentage for the merchantable stand characteristics. This lends confidence to the new treatment based conversion functions introduced in the 2005 model. Comparison of the R^2 scores by species group showed the 2005 update benefited the Aspen group the most, followed by the tolerant and intolerant. This further supports the species group stratification introduced in the 2005 update.

Table 20. Residual statistics generated from evaluation of the 1997 model.

Species Group	Stand Attribute	Units	n	Absolute Min	Absolute Max	Mean	Absolute Mean	Standard Deviation	R^2
Tolerant									
	Total								
	Dom. Height	m	728	0.0	0.9	0.0	0.2	0.2	0.995
	Av. Height	m	728	0.0	2.3	0.4	0.5	0.4	0.964
	Diameter	cm	728	0.0	14.2	1.0	2.5	2.0	0.650
	Density	stems/ha	728	0.1	9113.6	46.9	355.2	752.3	0.817
	Basal Area	m^2/ha	728	0.0	23.1	0.7	2.1	2.3	0.837
	Volume	m^3/ha	728	0.0	153.7	10.1	15.7	17.2	0.886
	Merch.								
	Av. Height	m	728	0.0	9.3	0.1	0.6	1.1	0.899
	Diameter	cm	728	0.0	13.1	0.1	2.2	2.0	0.654
	Density	stems/ha	728	0.0	1106.0	25.7	166.4	140.8	0.686
	Basal Area	m^2/ha	728	0.0	0.0	0.8	2.5	2.6	0.819
	Volume	m^3/ha	728	0.0	123.7	5.7	14.7	15.6	0.884
Intolerant									
	Total								
	Dom. Height	m	311	0.0	1.8	-0.1	0.2	0.1	0.996
	Av. Height	m	311	0.0	1.8	0.2	0.5	0.3	0.970
	Diameter	cm	311	0.0	6.0	-0.3	1.6	1.4	0.788
	Density	stems/ha	311	0.0	3950.6	-6.4	293.9	475.0	0.902
	Basal Area	m^2/ha	311	0.0	7.1	0.0	1.3	1.3	0.900
	Volume	m^3/ha	311	0.0	56.7	-1.1	9.1	9.2	0.918
	Merch.								
	Av. Height	m	311	0.0	8.7	-0.2	0.5	1.1	0.876
	Diameter	cm	311	0.0	11.8	-1.9	2.3	1.8	0.586
	Density	stems/ha	311	0.0	905.7	152.6	218.5	179.8	0.561
	Basal Area	m^2/ha	311	0.0	0.0	-0.1	1.8	1.7	0.883
	Volume	m^3/ha	311	0.0	55.0	-5.0	10.5	9.1	0.910
Aspen									
	Total								
	Dom. Height	m	125	0.0	1.3	-0.2	0.3	0.2	0.991
	Av. Height	m	125	0.0	2.0	0.1	0.5	0.4	0.971
	Diameter	cm	125	0.0	9.8	0.6	1.7	1.7	0.784
	Density	stems/ha	125	0.7	6908.2	160.3	337.0	767.4	0.906
	Basal Area	m^2/ha	125	0.0	23.1	1.4	3.1	3.7	0.788
	Volume	m^3/ha	125	0.2	160.9	12.7	20.5	25.6	0.822
	Merch.								
	Av. Height	m	125	0.0	9.1	-0.4	0.8	1.5	0.871
	Diameter	cm	125	0.0	12.4	-1.3	2.3	2.4	0.692
	Density	stems/ha	125	0.0	1776.5	227.9	368.1	388.6	0.533
	Basal Area	m^2/ha	125	0.0	0.0	1.6	3.8	4.1	0.745
	Volume	m^3/ha	125	0.0	145.4	5.2	20.3	22.4	0.830

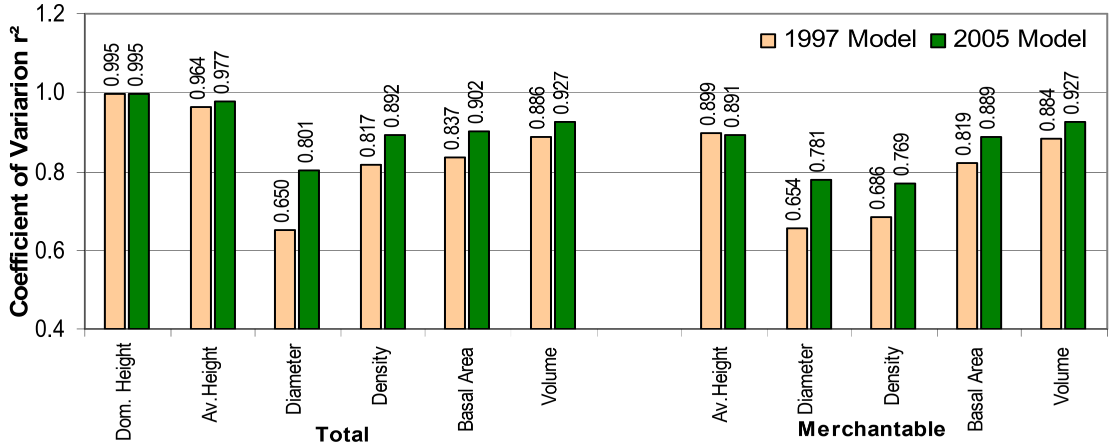

Figure 49. Comparison of the R² statistic compiled for the 1997 and 2005 models for the tolerant species group.

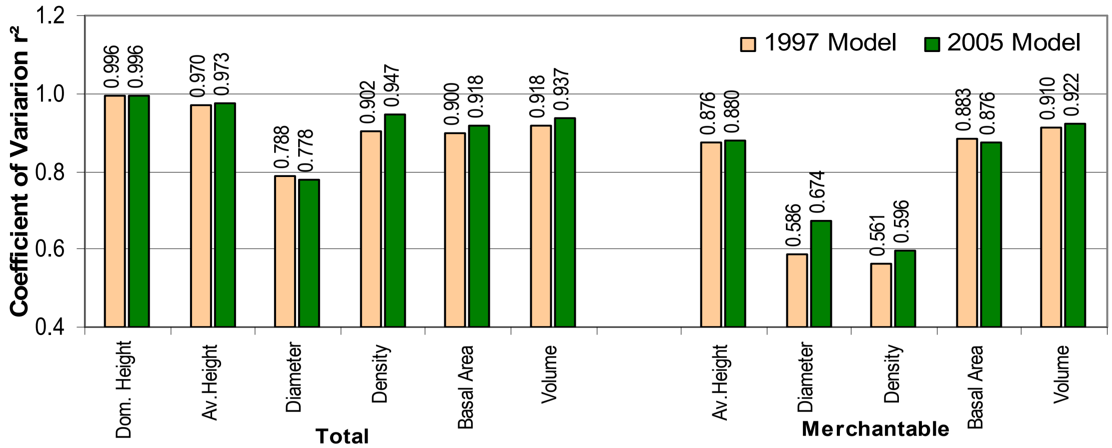

Figure 50. Comparison of the R² statistic compiled for the 1997 and 2005 models for the intolerant species group.

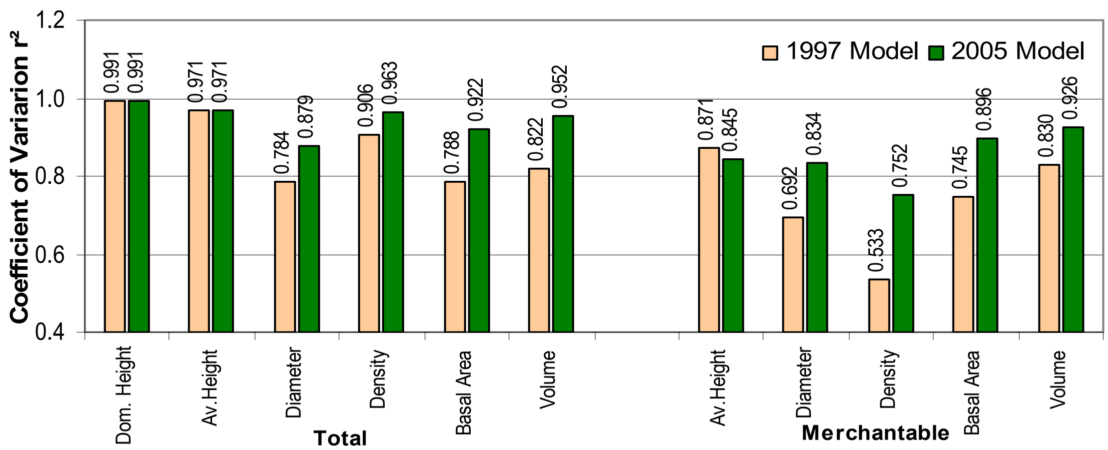

Figure 51. Comparison of the R² statistic compiled for the 1997 and 2005 models for the aspen species group.

6 Summary

The 2005 update of the hardwood growth and yield model was based on a database that had increased in size by approximately 50% since the 1997 model was developed. Although a few new PSPs may have been established, the majority of the increase is attributed to re-measurements of existing plots. In addition, the 2005 update compiled the hardwood Inventory PSPs for the purpose of model validation.

Natural unmanaged growth functions for average height (F03), total diameter (F04) and total density (F05) were each updated to varying degrees:

- The average height function (F03) was refit to the new data with no model changes.
- The total diameter model (F04) was modified to incorporate site index as a second independent variable and fit to the new data.
- The total density model (F05) was modified to incorporate species group using 'dummy' variables and refit to the new data.

The managed stand growth function changes included both model changes and the addition of new functions:

- The 2005 update created a new managed stand average height function (F03t) that used the same model as the unmanaged function yet was fit to the managed (PCT/CT) data observations.
- The managed stand diameter increment model (F18) was modified to incorporate species groups using 'dummy' variables. The resulting function showed the Aspen species group as having the highest diameter increment, the intolerant species group as lowest, and the tolerant increment fell in between the two.
- The post precommercial thinning artificial increase function for total diameter (F25) was refit to new data using the same model. The model now predicts change in diameter rather than a new post treatment diameter.

Aside from the addition of the new data, the conversion functions underwent three major changes:

- In the 2005 update of the merchantable and sawlog conversion functions, separate unmanaged and managed conversion functions were developed.
- The sawlog specification was changed from 18.24cm DBH and 10.16cm top to 25.4cm DBH and 20.32cm top.
- Merchantable and sawlog conversion functions were created for the stand frequency characteristic which was not done in the development of the 1997 model.

The evaluation of the new model compared the 2005 predictions against observations in the Inventory PSP database. The comparison showed that natural unmanaged growth function predictions were within expected ranges. In addition, it supports the founding assumptions of the model; they represent growth and development in normal fully stocked stands.

As a second component to the evaluation, age based predictions were compared to observations from the Research PSP database. Compilation of the resulting residual statistics showed the model performed well for all stand characteristics, species groups and all but one of the product classes. The exception was the sawlog product class where, estimates were less accurate, especially for the intolerant and Aspen species groups. Comparison of the compiled residual statistics to those compiled for the 1997 model showed the 2005 model performed on par or, in most cases, better than the 1997 model for all predicted stand characteristics by species group and product class.

7 Discussion

New data combined with new and updated growth functions translated into overall model improvement. The biggest change from the 1997 model was the introduction of species group variables that separated tolerant, intolerant and Aspen growth. The species group variables were added to the density function (F05) and the managed stand diameter growth function (F18).

Results of the species group separation in the density function (F05) showed the tolerant group changed little from the 1997 function. The intolerant group resulted in fewer stems and the Aspen resulted in more stems for any given diameter. At a reference diameter of 15cm, the predicted tolerant density decreased by 3%, the Aspen increased by 14%, and the intolerant decreased by 13%. The density predictions for larger diameter stands are less reliable because of limited data. This is especially true for Aspen where most natural unmanaged plots were less than 15cm in total diameter.

The updated managed stand diameter growth function (F18) showed a noticeable decrease in comparison to the 1997 model, especially at higher basal areas. The decrease was mainly due to removing mortality affects from the total average diameter increment compilation (see section 3.1). Among the newly represented species groups, the Aspen group showed the largest diameter increment predictions, the intolerant group the lowest while the tolerant group predictions were intermediate. At a reference site index of 16.5m and a total basal area of 15m²/ha the Aspen group increment was 16% higher (1.31cm vs. 1.52cm over 5 years) than the tolerant group and the intolerant group was 24% lower (1.31cm vs. 1.00cm over 5 years). Limited data in the Aspen group was a concern yet the data were well distributed across all sites and basal areas resulting in predictions consistent with underlying data. On the other hand, the intolerant group data, while more abundant, were skewed to the poor to average sites (site indices less than 18m). The few observations on better sites were far higher than predictions (Figure 19 on page 24). Based on this, caution is recommended when applying the tool to intolerant stands on better sites (> 18m site index).

The best measure of success of the update was in the evaluation of the 1997 and 2005 residual statistics generated by comparing model predictions to actual observations in the Research PSP database. The evaluation (using the R^2 statistic) showed that the updated model performed on par and in most cases better than the 1997 model. By far the biggest improvement over the 1997 model was its ability to better predict diameter and density (Figure 49, Figure 50 and Figure 51). The main contributing factors to the increased accuracy were the species group separation added to functions F05 and F18. The adoption of the model will improve the accuracy of forecasts for hardwood development in natural and managed stands for the province.

Acknowledgments

Thanks are due to former staff of the research section of the Nova Scotia Department of Natural Resources who initiated the growth and yield program as early as the 1960's. The data and concepts developed over the years have proved invaluable to current development work.

The Cooperative Forestry Research Unit (CFRU) of Maine is gratefully acknowledged for financially supporting this work. They helped fund the latest re-measurement of the research permanent sample plots from which the latest revision of the hardwood growth and yield model is based as well as subsequent development of the model.

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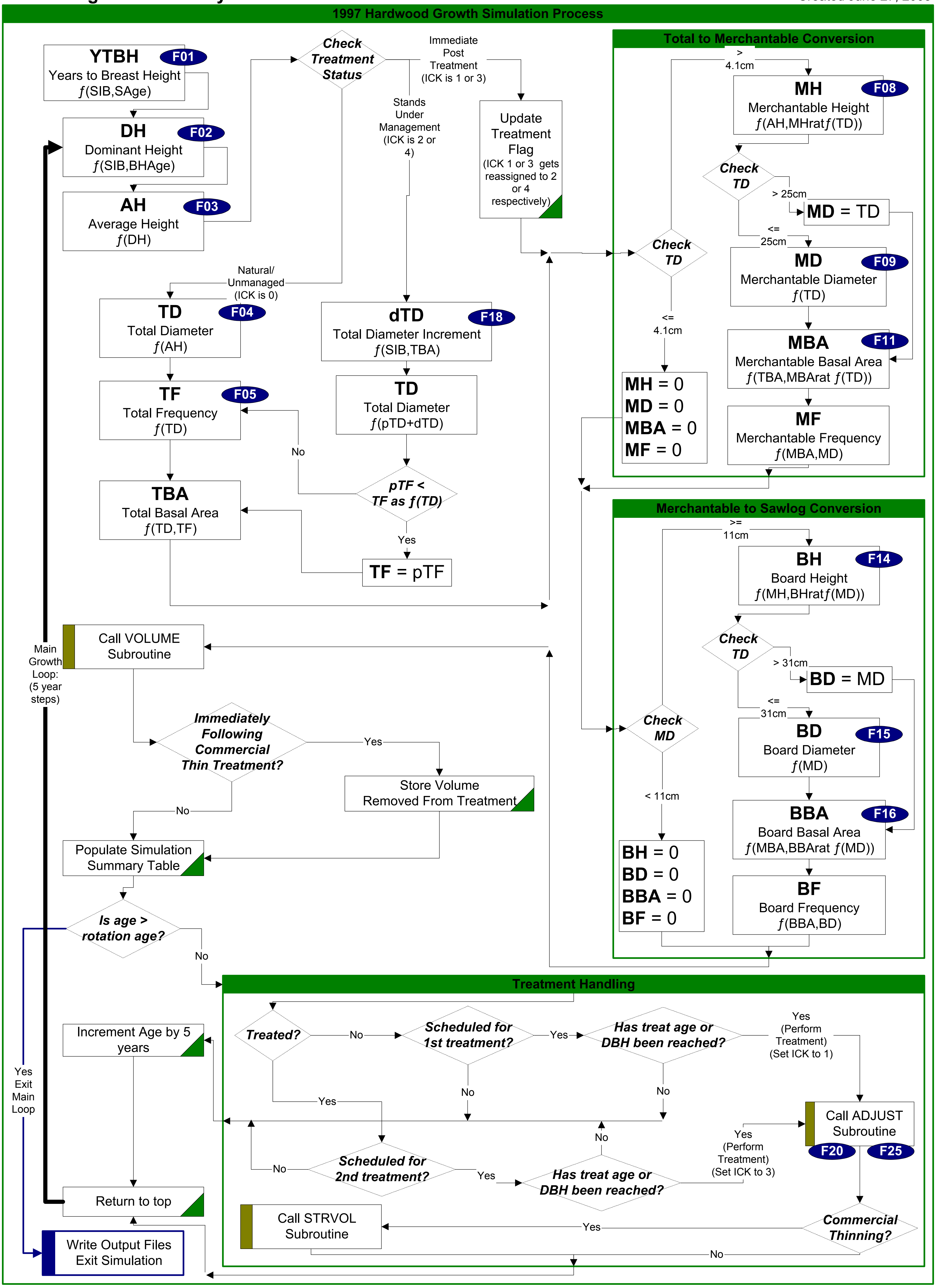
Appendix I: Detailed Growth Model Flow Diagrams

1997 Hardwood Growth and Yield Model

Flow Diagram of Primary Functions

Created June 27, 2005



Legend

FXX Refers to functions developed from PSP data; Details can be found in main document.

Code	Units	Description
SAge	years	Stump Age
BHAge	years	Breast Height Age
SIB	m	Site Index @ 50yrs (Breast Height Age)
YTBH	years	Years to Breast Height
DH	m	Dominant Height
AH	m	Average Total Height
TD	cm	Total Diameter at Breast Height
TF	stems/ha	Total Frequency
TBA	m²/ha	Total Basal Area
STRVOL	na	Subroutine to store volume before in CT treatment later used to calculate harvest from CT

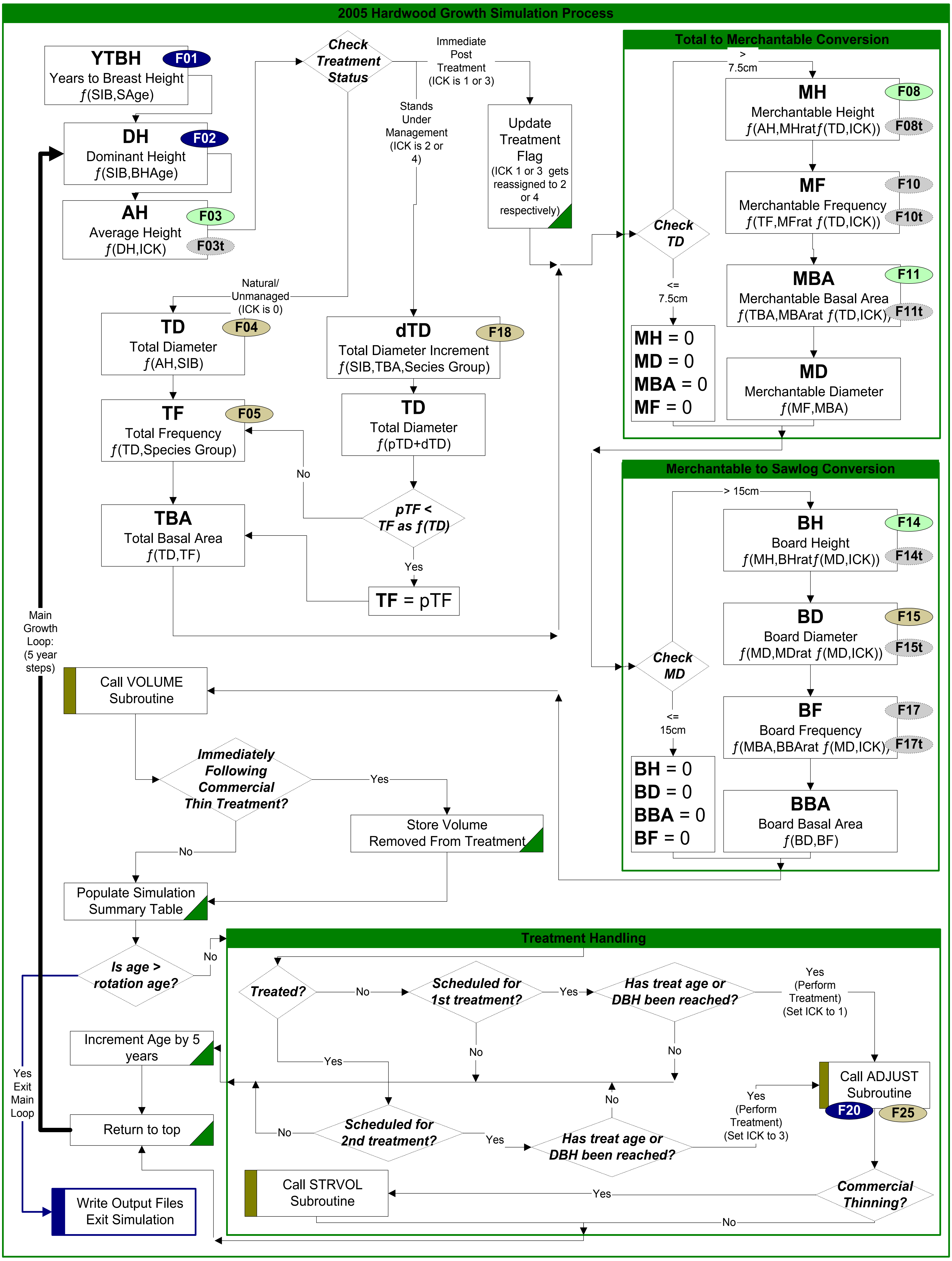
Code	Units	Description
MH	m	Average Height of Merchantable (>= 9.1cm dbh) trees
MD	cm	Merchantable Diameter at Breast Height
MF	stems/ha	Merchantable Frequency
MBA	m²/ha	Merchantable Basal Area
BH	m	Average Height of Sawlog (>= 18cm dbh) trees
BD	cm	Sawlog Diameter at Breast Height
BF	stems/ha	Sawlog Frequency
BBA	m²/ha	Sawlog Basal Area
CT	na	Commercial Thinning
ADJUST	na	Subroutine to adjust TF and artificially increase TD following Treatment

Code	Units	Descrip
dTD	cm	Total Diame
pTD	cm	Total Diame
pTF	stems/ha	Total Frequ
ICK	na	Treatment :
MHRat	%	Merchantak
MBARat	%	Merchantak
BHRat	%	Sawlog Hei
BBARat	%	Sawlog Bas
PCT	na	Percommer
VOLUME	na	Subroutine volumes us

2005 Hardwood Growth and Yield Model Update

Flow Diagram of Primary Functions

Created May 4, 2005



Legend

- FXX (dark blue) Functions not changed in 2005 update
- FXX (light green) Functions where existing model was refit with new data.
- FXX (tan) Functions where new model was created using new data.
- FXX (grey, dotted) New functions that did not exist in 1997.

Code	Units	Description	Code	Units	Description	Code	Units	Descrip
SAge	years	Stump Age	MH	m	Average Height of Merchantable (>= 9.1cm dbh) trees	dTD	cm	Total Diame
BHAge	years	Breast Height Age	MD	cm	Merchantable Diameter at Breast Height	pTD	cm	Total Diame
SIB	m	Site Index @ 50yrs (Breast Height Age)	MF	stems/ha	Merchantable Frequency	pTF	stems/ha	Total Frequ
YTBH	years	Years to Breast Height	MBA	m²/ha	Merchantable Basal Area	ICK	na	Treatment S
DH	m	Dominant Height	BH	m	Average Height of Sawlog (>= 18cm dbh) trees	MHRat	%	Merchantab
AH	m	Average Total Height	BD	cm	Sawlog Diameter at Breast Height	MBARat	%	Merchantab
TD	cm	Total Diameter at Breast Height	BF	stems/ha	Sawlog Frequency	BHRat	%	Sawlog Hei
TF	stems/ha	Total Frequency	BBA	m²/ha	Sawlog Basal Area	BBARat	%	Sawlog Bas
TBA	m²/ha	Total Basal Area	CT	na	Commercial Thinning	PCT	na	Percommer
STRVOL	na	Subroutine to store volume before in CT treatment later used to calculate harvest from CT	ADJUST	na	Subroutine to adjust TF and artificially increase TD following Treatment	VOLUME	na	Subroutine volumes us