YIELD FUNCTIONS AND TABLES FOR MIXEDWOOD STANDS OF NORTHWESTERN ONTARIO

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ABSTRACT

Data from 347 permanent growth plots in the mixedwood stands of northwestern Ontario were used to develop yield functions and tables. The resulting yield functions and tables may serve as preliminary growth and yield information for forest management planning.

RÉSUMÉ

À partir des données de 347 placettes d'échantillonnage permanentes se trouvant dans les peuplements de forêt mixte du nord-ouest de l'Ontario, on a construit de équations de production et des tableaux. Les tables et équations de production établies peuvent fournir des informations préliminaires sur l'accroissement et la production pour la planification de l'aménagement forestier.

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Cover photo: A spruce-fir stand in northwestern Ontario.

INTRODUCTION

About 3 million hectares of Ontario's productive forest lands are classified as mixedwood forest type. Because of the Canadian wood supply situation and the increased demand for both wood and recreational use of forest lands, greater demand will be placed on the mixedwood forest types of Ontario.

No definitive management plan can be developed for a complex forest type without sufficient information on its extent, composition, growth and yield. Forest managers require better information on stand productivity under various management intensities. Although several major studies have been undertaken on this forest type over the last 40 years, little growth and yield information has been published to date.

One of the earlier growth and yield studies on northwestern Ontario's mixedwood stands originated in 1948. Several pulp and paper companies jointly requested the Ontario District of the then Forestry Branch to provide growth and yield information on forest types in the Nipigon area (Bedell and MacLean 1952). The companies agreed to assume responsibility for data collection while the Forestry Branch assumed responsibility for data compilation and analysis.

In 1974 it was further agreed that the Canadian Forestry Service's Forest Management Institute would prepare separate inventory-oriented stand development tables for American Can of Canada Ltd. and Kimberly-Clark of Canada Ltd. Once this primary objective was met, either the Forest Management Institute or the Great Lakes Forest Research Centre (now the Great Lakes Forestry Centre) would process the data to provide further growth and yield information.

Evert (1975) published separate stand development curves and tables for each company by forest type, but without stratification by site. This useful report was well received by both companies involved and thus satisfied the primary objective of the above-mentioned agreement. Evert (1976a) further prepared variable density yield tables for the jack pine (*Pinus banksiana* Lamb.) cover type for three broad site classes. He also developed (Evert 1976b) equations and tables showing loss of volume as a result of regular mortality for the five cover types within pulpwood stands.

Although Evert's (1975, 1976a, 1976b) reports provide needed growth and yield information, even more useful material may be derived from such a data set. The purpose of this report is to present yield functions and tables derived for the entire data set and all cover types combined. These tables provide generalized yield information applicable to a broader range of site conditions and species composition than that indicated by Evert (1975). In addition, the equations will facilitate computer processing of such yield information.

MATERIALS AND METHODS

Data sets were identical to those used by Evert (1975), and consisted of the tallies of 347 permanent growth plots (0.02 to 0.40 ha in size) maintained by the two companies, American Can of Canada Ltd. and Kimberly-Clark of Canada Ltd. Each plot had been measured from two to four times, mostly at 5-year intervals. Plot data included: cover type (see Appendix A), broad site classes according to Hills' (1954) classification, initial stand age, plot number, number of trees, species code, and diameter of all trees > 1.5 cm DBH. Appendix B is a statistical summary of the initial measurement of the two data sets plus the estimated stand and individual tree characteristics as described below:

A. Site index (at age 50). Since site information recorded was not suitable for quantitative analysis and since no height data were collected, site index was estimated from initial average (quadratic) diameter-age relationship as follows:

a) site index was expressed as a function of stand average diameter and age for the major species in Ontario from Plonski's (1974) yield tables as:

$$S = b_1 D^{b_2} (1-e^{-b_3 T})^{b_4} \qquad (1)$$

where S = site index
D = average stand diameter
T = stand age
e = base of natural logarithms, and
bs = parameters of the model.

b) The resulting expressions based on the above model (see Appendix C) were used to estimate site index for each plot per cover type, i.e., the site index expression for black spruce was used for the black spruce cover type; that of jack pine was used for the jack pine, mixed softwood and mixedwood cover types; and that of aspen was used for the hardwood cover type.

B. Stand height. Stand height per plot was estimated from site index as above and in the site index expressions for major species in Ontario (Payandeh 1977), as:

$$H = b_1 S^{b_2} (1-e^{-b_3 T})^{b_4} S^{b_5} \qquad (2)$$

where: H = average stand height and other symbols are defined as before.

Here again, the above expression was used depending on plot cover type, i.e., the expression for black spruce was used for the black spruce cover type; that of jack pine was used for the jack pine, mixed softwood and mixedwood cover types; and that of aspen was used for the hardwood cover type.

C. Tree height. Tree height was estimated in a manner similar to that used in A above; equations expressing height as a function of diameter and site index were derived from Plonski's (1974) yield tables and were based on the following model:

$$H = 1.37 + b_1 S^{b_2} (1-e^{-b_3 D})^{b_4} \qquad (3)$$

Individual tree heights were approximated by substituting individual tree diameters in the above model. Such expressions were used for different cover types as in A and B above (see Appendix C).

D. Tree volume. Total and merchantable volume (trees $\geqslant$ 10 cm DBH, 30 cm stump height and up to 7.5 cm top diameter) of individual trees were calculated according to Honer's (1967) tree volume equations and were based on species, DBH and estimated tree height as in C above.

The above calculations were carried out for all plots and each measurement period, except that site index estimation was based on the initial measurement only. All final calculations were converted to metric units.

ANALYSIS AND RESULTS

Both linear and nonlinear (cf. Draper and Smith 1966) regression models were used to develop equations for various yield characteristics. In all cases nonlinear models produced better fit and/or more reasonable functional forms than linear models. For each yield characteristic several models were examined and the final equation was chosen on the basis of its R^2, standard error and % bias values.

Much effort was concentrated on modeling basal area and volume. About a dozen regression models ranging from the Richards growth function (Richards 1959) to a seven-parameter model containing various forms of site index, stand density (i.e., number of trees/ha) and stand age as explanatory variables were tried. These models were examined for both data sets, i.e., for the American Can and Kimberly-Clark data. They were also tested for the combined data (all measurements) and for the initial measurement only.

Screening of the resulting equations indicated that inclusion of all measurement data did not improve the fit appreciably; therefore, the remaining analyses were applied to the initial measurement data only. The resulting equations for the American Can and Kimberly-Clark data were not significantly different; therefore, the two data sets were combined. This resulted in a significant improvement in the regression fit owing to a more balanced data set, i.e., better coverage of the range of stand age, site index, stand density, etc. All subsequent yield analyses were carried out on the combined data set and for the first measurement only.

Table 1 summarizes the final regression equations for the various yield characteristics, along with their respective R^2, standard errors and % bias. Total basal area and volume were initially expressed as functions of site index,

Table 1. Nonlinear regression equations expressing various yield characteristics of mixedwood stands in northwestern Ontario[a].

Yield characteristic		R^2	Standard error	% bias
Average stand height (m)	$H = 3.571\ S^{.648}(1-e^{-.0323\ T})^{11.79}\ S^{-.74}$	0.92	1.2	0.16
Number of trees/ha	$N = 16814.2\ S^{-.767}(1-e^{-.028\ T})^{-1.8}e^{-.0057\ T}$	0.78	974.	-2.30
Total basal area (m^2/ha)[b]	$G_t = 22.26\ S^{.306}(1-e^{-.028\ T})^{-.927}e^{-.0029\ T}(1-e^{-.037\ T})^{16.62}\ S^{-.665}$	0.74	4.51	0.40
Merchantable basal area (m^2/ha)[c]	$G_m = 0.964\ G_t(1-e^{-.0682\ T})^{2.058}$	0.94	2.10	- .13
Total volume (m^3/ha)[b]	$V_t = 47.74\ S^{.848}(1-e^{-.028\ T})^{-1.174}e^{-.0037\ T}(1-e^{-.037\ T})^{21.04}\ S^{-.665}$	0.84	42.85	.22
Merchantable volume (m^3/ha)[c]	$V_m = 0.894\ V_t(1-e^{-.063\ T})^{2.822}$	0.96	21.18	-2.2

[a] Based on the initial measurement of 347 permanent sample plots established and maintained by the American Can Company of Canada Ltd. and Kimberly-Clark Company of Canada Ltd. since 1948.

[b] Includes basal area and volume of all trees 1.5 cm DBH in the stand.

[c] Includes gross basal area or volume of trees 10 cm DBH in the stand. Volume based on 30-cm stump height and up to 7.5-cm top diameter.

H = average stand height (m)

S = site index (m)

T = stand age (years)

N = number of trees/ha

G_t = total basal area (m^2/ha)

G_m = merchantable basal area (m^2/ha)

V_t = total volume (m^3/ha)

V_m = merchantable volume (m^3/ha)

stand age and density. However, to avoid the need for variable density yield tables, two-stage regression analysis was employed to express total basal area and volume as function of site index and stand age, as shown in Table 1. A set of yield tables for site indices of 5, 10, 15, 20, 25 and 30 m was generated on the basis of the yield equations. These tables are given in Appendix D. Figure 1 shows stand development of an average site, i.e., site index = 15 m, for the major yield characteristics.

SUMMARY

Nonlinear regression equations based on data from 347 permanent growth plots from northwestern Ontario were developed for the main stand yield characteristics. Since the data lacked a quantitative measure of site productivity or stand height, site index/plot was approximated on the basis of stand diameter growth according to Plonski's (1974) yield tables. Estimates of stand and individual tree heights were then derived by means of regression equations expressing stand-height as a function of site index and average stand diameter, respectively.

Numerous regression models were considered for various yield characteristics, but initial emphasis was placed on modeling basal area and volume. The final regression equations were chosen on the basis of their R^2, standard error, % bias values and functional forms.

The results presented here indicate the effect of site productivity on mean annual increment and its inverse effect on the age at which mean annual increment culminates. Rotation age is often chosen to coincide with the age at which mean annual volume increment culminates, because at this age the stand will yield the maximum possible volume/ha per year. Hence, the results given here may be used to determine both the rate of volume increment and rotation age for a given site.

The equations and tables presented here should complement Evert's (1975, 1976a, 1976b) reports by providing growth and yield information for the pulpwood stands of northwestern Ontario. The present results, however, should have a broader application since they were derived from the entire data set and are based on models that behave well upon extrapolation. No attempt was made to develop separate yield functions for different merchantability standards, mainly because the future trend is towards total volume and/or biomass utilization.

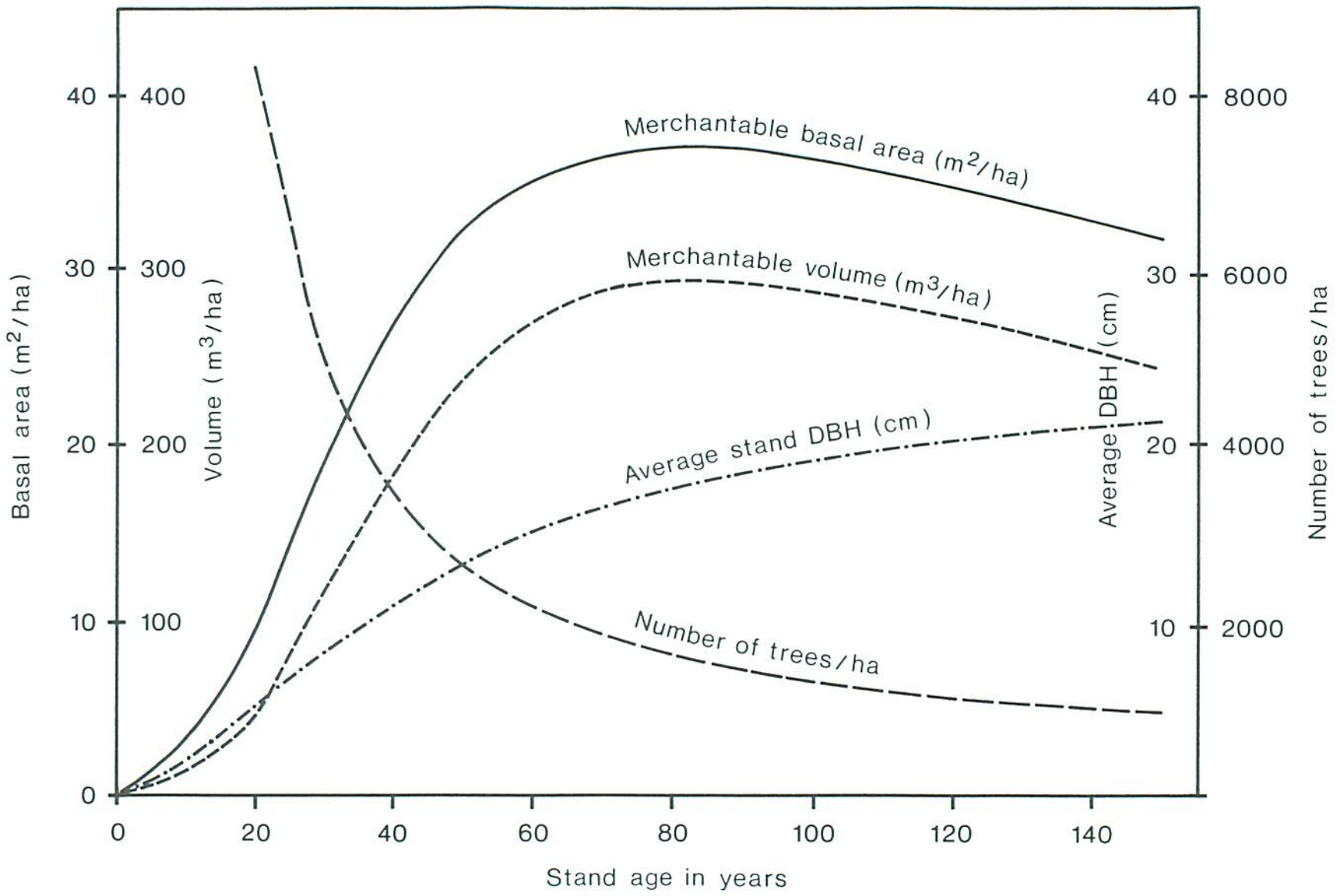

Figure 1. Plotting of the main yield components for the mixedwood stands of northwestern Ontario. Site index = 15 m.

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APPENDICES

APPENDIX A

Main cover types and species description included in the data sets.

1. Cover types	Description
Black spruce	75% or more black spruce
Jack pine	75% or more jack pine
Mixed softwood	25% to 75% jack pine, the remainder spruce
Mixedwood	25% to 75% softwood, the remainder hardwood
Hardwood	75% or more hardwood

2. Species

Common name	Scientific name
Black spruce	*Picea mariana* (Mill.) B.S.P.
White spruce	*Picea glauca* (Moench) Voss
Jack pine	*Pinus banksiana* Lamb.
Balsam fir	*Abies balsamea* (L.) Mill.
White cedar	*Thuja occidentalis* L.
Eastern larch	*Larix laricina* (Du Roi) K. Koch
Trembling aspen	*Populus tremuloides* Michx.
Balsam poplar	*Populus balsamifera* L.
White birch	*Betula papyrifera* Marsh.

APPENDIX B

Statistical summary of the initial measurements of the two data sets (American Can and Kimberly-Clark companies) used in developing yield tables for pulpwood stands of northwestern Ontario.

Stand characteristic	Minimum	Maximum	Statistical mean	Variance	Coefficient of variation (%)
		Data set #1, 229 plots (American Can of Canada Ltd.)			
Diameter[a] (cm)	4.2	26.6	13.0	19.9	34.3
Height (m)	3.5	21.9	11.7	15.4	33.7
Age[a] (year)	28	200	83	1429	45.7
Site index (m)	2.7	21.8	11.5	15.4	34.2
No. of trees/ha	580	12,565	3297	5146956	68.8
Total basal area (m^2/ha)	8.4	56.6	33.4	90.1	28.4
Merchantable basal area (m^2/ha)	.2	55.3	28.5	150.5	43.0
Total volume (m^3/ha)	25.1	675.3	254.3	13700	46.0
Merchantable volume (m^3/ha)	.8	638.4	211.1	14852	57.7
		Data set #2, 118 plots (Kimberly-Clark Co. of Canada Ltd.)			
Diameter[a] (cm)	7.8	29.6	15.1	15.4	25.9
Height (m)	8.5	27.4	14.7	11.4	23.0
Age[a] (year)	34	170	82	836	35.4
Site index (m)	5.2	22.8	13.2	10.3	24.3
No. of trees/ha	630	7684	2389	1866146	57.2
Total basal area (m^2/ha)	16.5	54.4	35.7	45.3	18.9
Merchantable basal area (m^2/ha)	9.8	53.2	32.3	52.9	22.5
Total volume (m^3/ha)	114.1	593.0	277.0	6219	28.5
Merchantable volume (m^3/ha)	41.2	559.9	232.9	7308	36.7

[a] Only diameter and stand age were based on actual field measurements. Other stand characteristics were estimated or calculated as described in the text.

APPENDIX C

A. Equations expressing site index as a function of average stand diameter and age, derived from Plonski's yield tables and used here to estimate site index/plot[a].

Species	Site index expression[b]	Cover types used for
Black spruce	$S = .1337\ D^{1.434}\ (1-e^{-.0176\ T})^{-2.141}$	black spruce
Jack pine	$S = 1.026\ D^{.8859}\ (1-e^{-.0326\ T})^{-1.702}$	jack pine, mixed softwood and mixedwood
Aspen	$S = .4433\ D^{.9798}\ (1-e^{-.00936\ T})^{-1.042}$	hardwood

B. Equations expressing stand height as a function of site index and stand diameter, derived from Plonski's yield tables and used here to calculate individual tree heights[b].

Species	Height equation[c]	Cover types used for
Black spruce	$H = 1.37 + 19.899\ S^{.122}\ (1-e^{-.0899\ D})^{1.934}$	black spruce
Jack pine	$H = 1.37 + 23.507\ S^{.2607}\ (1-e^{-.0243\ D})^{.9933}$	jack pine, mixed softwood and mixedwood
Aspen	$H = 1.37 + 10.2313\ S^{.363}\ (1-e^{-.0778\ D})^{1.593}$	hardwood

[a] Where S = estimated site index (m), D = average stand diameter (cm) and T = stand age (years)

[b] Where H = estimated stand height (m), S = site index (m) and D = average stand diameter (cm)

[c] Since the equations were based on yield tables rather than actual field data, regression statistics such as R^2 or error mean squares are of little consequence, and therefore are omitted.

APPENDIX D

Table 1. Yield per hectare of mixedwood stands in northwestern Ontario. Site index = 5 m.

Stand age (yr)	Avg DBH[a] (cm)	Avg ht (m)	No. of trees (>1.5 cm)	Basal area (m^2)		Volume (m^3)		PAI (m^3)	MAI (m^3)
				(>1.5 cm)	(≥10 cm)	(>1.5 cm)	(≥10 cm)		
20	1.1	0.7	19949	1.9	1.0	4.4	1.5	0.0	0.1
30	2.5	1.8	11350	5.8	4.2	18.2	10.2	0.9	0.3
40	4.2	3.1	7892	10.8	9.0	39.8	28.1	1.8	0.7
50	5.7	4.5	6096	15.5	13.9	63.1	49.8	2.2	1.0
60	7.0	5.7	5014	19.3	17.9	83.2	69.7	2.0	1.2
70	8.1	6.7	4294	22.0	20.8	98.1	84.8	1.5	1.2
80	8.9	7.5	3779	23.7	22.6	108.0	94.8	1.0	1.2
90	9.6	8.1	3390	24.6	23.6	113.5	100.5	0.6	1.1
100	10.2	8.6	3083	25.1	24.1	115.8	103.0	0.3	1.0
110	10.6	9.0	2831	25.1	24.1	115.9	103.3	0.0	0.9
120	11.0	9.3	2618	24.8	23.9	114.5	102.2	-0.1	0.9
130	11.3	9.5	2435	24.4	23.6	112.1	100.2	-0.2	0.8
140	11.6	9.6	2273	23.9	23.1	109.2	97.6	-0.3	0.7
150	11.8	9.7	2128	23.4	22.5	105.9	94.7	-0.3	0.6

[a] Average stand DBH is based on the estimated total basal area and the number of trees/ha to maintain full compatibility.

(cont'd)

Table 2. Yield per hectare of mixedwood stands in northwestern Ontario. Site index = 10 m.

Stand age (yr)	Avg DBH[a] (cm)	Avg ht (m)	No. of trees (>1.5 cm)	Basal area (m^2)		Volume (m^3)		PAI (m^3)	MAI (m^3)
				(>1.5 cm)	(≥10 cm)	(>1.5 cm)	(≥10 cm)		
20	3.1	3.3	11698	9.1	4.8	44.3	15.4	0.0	0.8
30	5.6	5.8	6656	16.6	12.0	94.8	53.4	3.8	1.8
40	7.9	8.2	4628	22.9	19.2	142.4	100.5	4.7	2.5
50	9.9	10.1	3575	27.4	24.6	178.9	141.3	4.1	2.8
60	11.5	11.7	2940	30.3	28.2	203.3	170.3	2.9	2.8
70	12.7	12.9	2518	32.0	30.3	217.4	187.7	1.8	2.7
80	13.7	13.8	2216	32.7	31.3	223.9	196.5	0.9	2.5
90	14.5	14.5	1988	32.9	31.6	225.1	199.3	0.3	2.2
100	15.2	15.0	1808	32.6	31.4	222.8	198.2	-0.1	2.0
110	15.7	15.4	1660	32.1	30.9	218.4	194.7	-0.4	1.8
120	16.2	15.7	1536	31.5	30.3	212.7	189.9	-0.5	1.6
130	16.6	15.9	1428	30.7	29.6	206.3	184.3	-0.6	1.4
140	16.9	16.0	1333	30.0	28.9	199.5	178.3	-0.6	1.3
150	17.2	16.1	1248	29.1	28.1	192.7	172.2	-0.6	1.2

[a] Average stand DBH is based on the estimated total basal area and the number of trees/ha to maintain full compatibility.

(cont'd)

APPENDIX D (cont'd)

Table 3. Yield per hectare of mixedwood stands in northwestern Ontario. Site index = 15 m.

Stand age (yr)	Avg DBH[a] (cm)	Avg ht (m)	No. of trees (>1.5 cm)	Basal area (m^2)		Volume (m^3)		PAI (m^3)	MAI (m^3)
				(>1.5 cm)	(≥10 cm)	(>1.5 cm)	(≥10 cm)		
20	5.1	6.7	8561	17.8	9.3	125.2	43.7	0.0	2.2
30	8.3	10.2	4871	26.4	19.1	205.4	115.7	7.2	3.4
40	11.0	13.1	3387	32.2	27.0	265.0	187.0	7.1	4.7
50	13.2	15.3	2616	35.9	32.2	303.2	239.5	5.3	4.8
60	15.0	17.1	2152	37.8	35.2	324.3	271.7	3.2	4.5
70	16.3	18.3	1843	38.7	36.6	333.4	287.9	1.6	4.1
80	17.4	19.3	1622	38.8	37.1	334.3	293.4	0.6	3.7
90	18.3	20.0	1455	38.4	36.9	330.1	292.3	-0.1	3.3
100	19.1	20.5	1323	37.7	36.3	322.8	287.1	-0.5	2.9
110	19.7	20.9	1215	36.9	35.6	313.8	279.7	-0.7	2.5
120	20.2	21.2	1124	36.0	34.7	303.8	271.2	-0.9	2.3
130	20.7	21.4	1045	35.0	33.8	293.5	262.2	-0.9	2.0
140	21.1	21.5	975	34.1	32.8	283.1	253.0	-0.9	1.8
150	21.5	21.7	913	33.1	31.9	272.8	243.9	-0.9	1.6

[a] Average stand DBH is based on the estimated total basal area and the number of trees/ha to maintain full compatibility.

APPENDIX D (cont'd)

Table 4. Yield per hectare of mixedwood stands in northwestern Ontario. Site index = 20 m.

Stand age (yr)	Avg DBH[a] (cm)	Avg ht (m)	No. of trees (>1.5 cm)	Basal area (m^2)		Volume (m^3)		PAI (m^3)	MAI (m^3)
				(>1.5 cm)	(≥10 cm)	(>1.5 cm)	(≥10 cm)		
20	7.0	10.3	6860	26.5	13.9	236.3	82.4	0.0	4.1
30	10.7	14.5	3903	34.9	25.2	333.8	188.0	10.6	6.3
40	13.7	17.7	2714	39.8	33.4	395.3	278.9	9.1	7.0
50	16.1	20.2	2096	42.5	38.2	429.1	339.0	6.0	6.8
60	18.0	22.0	1724	43.7	40.6	443.7	371.7	3.3	6.2
70	19.4	23.3	1477	43.8	41.5	446.0	385.2	1.4	5.5
80	20.6	24.3	1300	43.4	41.5	440.6	486.7	0.2	4.8
90	21.6	25.0	1166	42.7	41.0	430.7	381.3	-0.5	4.2
100	22.4	25.6	1060	41.7	40.9	418.3	372.0	-0.9	3.7
110	23.1	25.9	974	40.7	39.1	404.7	360.8	-1.1	3.3
120	23.6	26.2	900	39.5	38.1	390.6	348.6	-1.2	2.9
130	24.2	26.4	837	38.4	37.0	376.4	336.3	-1.2	2.6
140	24.7	26.6	782	37.3	36.0	362.5	324.0	-1.2	2.3
150	25.1	26.7	732	36.2	34.9	349.0	312.0	-1.2	2.1

[a] Average stand DBH is based on the estimated total basal area and the number of trees/ha to maintain full compatibility.

APPENDIX D (concl.)

Table 5. Yield per hectare of mixedwood stands in northwestern Ontario. Site index = 25 m.

Stand age (yr)	Avg DBH[a] (cm)	Avg ht (m)	No. of trees (>1.5 cm)	Basal area (m^2)		Volume (m^3)		PAI (m^3)	MAI (m^3)
				(>1.5 cm)	(≥10 cm)	(>1.5 cm)	(≥10 cm)		
20	8.8	14.0	5777	34.8	18.2	369	129	0.0	6.4
30	12.8	18.7	3287	42.3	30.6	472	266	13.7	8.9
40	16.0	22.2	2285	46.2	38.7	529	373	10.7	9.3
50	18.6	24.7	1765	48.0	43.2	555	438	6.5	8.8
60	20.6	26.6	1452	48.5	45.1	561	470	3.2	7.8
70	22.2	28.0	1244	48.1	45.6	556	480	1.0	6.9
80	23.5	29.0	1095	47.3	45.2	544	477	-0.3	6.0
90	24.5	29.7	982	46.2	44.4	528	467	-1.0	5.2
100	25.3	30.2	893	45.0	43.3	511	454	-1.3	4.5
110	26.1	30.6	820	43.8	42.1	492	439	-1.5	4.0
120	26.7	30.9	758	42.5	40.9	474	423	-1.6	3.5
130	27.3	31.1	705	41.2	39.7	456	408	-1.6	3.1
140	27.8	31.2	658	40.0	38.6	439	392	-1.5	2.8
150	28.3	31.3	616	38.8	37.4	422	378	-1.5	2.5

[a] Average stand DBH is based on the estimated total basal area and the number of trees/ha to maintain full compatibility.