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MERCHANTABLE VOLUME CONVERSION FACTORS AND TAPER EQUATIONS FOR COMMERCIALTREE SPECIES OF ONTARIO

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INTRODUCTION

The merchantable volume of single trees or stands is widely required in forestry. Many lumber companies, for example, base their operations on the merchantable volume they obtain from the forest. Merchantable volume of a tree can be defined as the volume of a stem from a given stump height to a given merchantable diameter or to a specified height along the stem. For a given utilization standard this volume changes with the size of the stem in both its absolute and relative (percentage) values. This makes it necessary to develop prediction equations for different utilization standards as well as for different tree sizes. Taper curves, volume equations for a given diameter of utilization, and ratio expressions for variable merchantable diameters and merchantable heights are the three main approaches to estimate merchantable volume. Examples of studies using these concepts are by Behre (1927), Bennett et al. (1959), and Burkhart (1977), respectively. Taper equations are also useful for calculating stem volume, and for estimating the efficiency of sawmilling and lumber production operations.

In an earlier report (Alemdag 1988), the ratio concept was studied in detail. A method for merchantable volume estimation was developed and taper equations were derived for one softwood species and one hardwood species in Ontario. Using the same method, the aim of the present report is to present merchantable volume conversion factors for 28 commercial tree species in Ontario. The species studies are listed in Table 1.

DATA

The data employed in this study were collected in 1978-1983 as a part of two biomass studies. A summary is presented in Table 2. All sample trees were cut at a fixed stump height of 0.30 m. In addition to breast height diameter, diameters at three locations along the stem were measured: one where diameter outside bark was 9.2 cm, and the others at 1/3 and 2/3 of the height from ground level to the 9.1 cm point. Heights to these three locations were also taken. Later, the volume of each of these 1/3 sections was calculated.

It should be noted that here, diameters are expressed in centimetres, heights (including stump height) in metres, and volumes in cubic metres (inside bark, regardless of decay and defect). Thus:

- D = breast height diameter at 1.30 m, outside bark
- d = merchantable top diameter, inside bark
- H = total tree height
- h = merchantable height (height from ground level to a specified utilization limit)
- hs = stump height
- VT = total stem volume from ground level to the tip of the tree
- VM = merchantable volume (volume from stump height to a specified utilization limit)
- VS30 = stump volume at 0.30 m stump height
- VS = stump volume at a given stump height
- VP = top volume above a given merchantable top diameter, or, above a given merchantable height
- VL = ground-to-limit volume (volume from ground level to a specified utilization limit)

Figure 1 illustrates these variables.

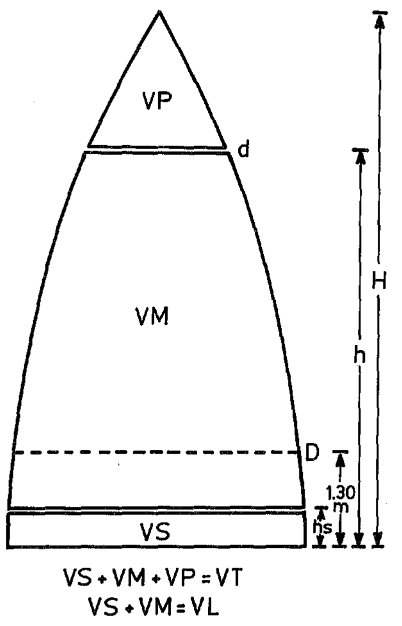

Figure 1. Volume components of a stem and its dimensional measurements.

METHOD

Because the method of developing merchantable volume conversion factors as ratios was explained in detail by Alemdag (1988), only a summary is provided here. When volume distribution is studied in two trees of the same shape (assumed to be proportionally similar in all dimension) it will be seen that volume ratio remains the same for a given h/H ratio and approximately the same for a given d/D ratio. Figure 2 verifies this theorem, illustrating the distribution of volume ratios over relative diameters and relative heights using data from white spruce.

In order to obtain the merchantable volume/total stem volume ratio, the following procedure is followed sequentially: (1) estimate ground-to-limit volume ratio; (2) estimate stump volume ratio; and, (3) estimate merchantable volume ratio. After the merchantable volume ratio is determined, it is used as a conversion factor with a given total stem volume for calculating the merchantable volume.

RESULTS

Results of the above procedure are provided below:

(1) The ground-to-limit volume ratios (VL/VT, or K) were expressed as a function of d/D or h/H, where d and he are flexible values. Based on the relationships shown in Figure 2, several mathematical models were tested and the most promising, as shown in Table 3, were used in the subsequent analyses. These are conditioned models, because K is 1 when d/D is zero or h/H is 1. The linear regression technique was

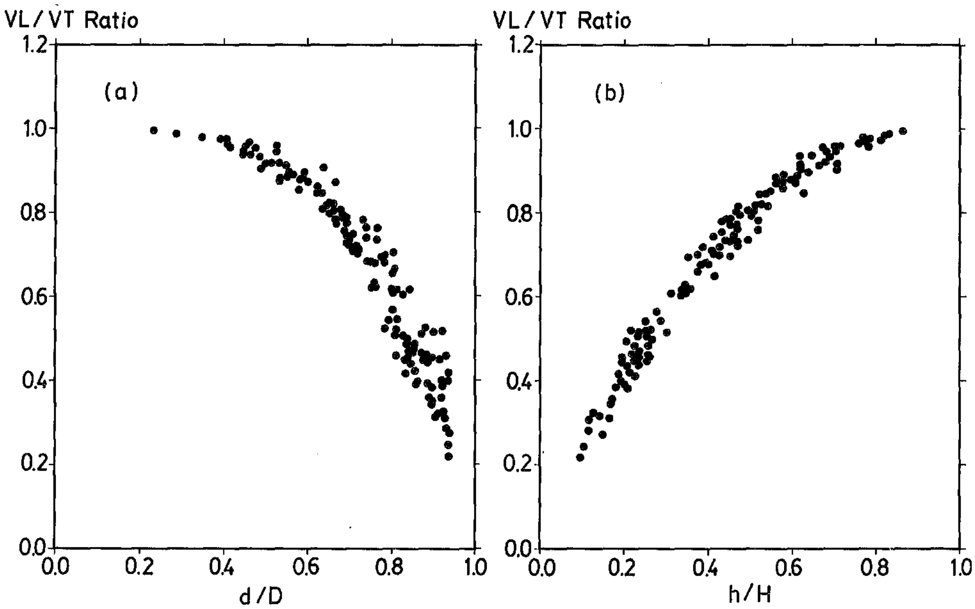

Figure 2. Scatterdiagrams showing the relationships of VL/VT ratios with (a) d/D ratios, and (b) h/H ratios: an example with white spruce.

used to develop the equations and the results of the analyses for each species were evaluated by their fit index (FI) (Alemdag 1986) and the standard error of estimate (SEE%) values. Models 1 and 3 produced almost identical results and also better results than that of Model 2. Similarly, Models 4 and 6 performed better than Model 5. For these reasons Model 1 was adopted for the d/D expression and Model 4 for the h/H expression.* These models for all species, together with their regression coefficients and statistical data, are presented in Table 4.

(2) Estimating stump volume ratios at the 0.30 m stump height (VS30/VT) as a function of D and H, or VT, was not feasible because of the stump volume ratio's weak and insignificant relationships with these values, possibly because of inconsistent butt flare. For this reason the mean values of these ratios were adopted for each species as shown in Table 5. However, as these are averages for the 0.30 m stump height and because stump volume ratio may be required at other stump heights, a conversion factor (p) was developed for this purpose by a geometrical method in which the stump was assumed to be the frustum of a neiloid (Alemdag 1988). This factor for all species is

$$p = 3.610 \bullet hs - 0.922 \bullet hs^2 \qquad (1)$$

and the stump volume ratio at a given stump height for each species is

$$VS/VT = (VS30/VT) \bullet p \qquad (2)$$

(3) Establishing the merchantable volume ratio (VM/VT) or the merchantable volume conversion factor for a given merchantable top diameter or merchantable height is done simply by taking the difference between the ground-to-limit volume ratio and the stump volume ratio. Hence:

$$VM/VT = VL/VT - VS/VT, \text{ or} \qquad (3)$$

$$VM/VT = VL/VT - (VS30/VT) \bullet p \qquad (4)$$

$$VM/VT = 1 + b_1 \bullet (d/D)^{b_2} - VS30/VT \bullet (3.610 \bullet hs - 0.922 \bullet hs^2) \qquad (5a)$$

$$VM/VT = 1 + c_1 \bullet (1 - h/H)^{c_2} - VS30/VT \bullet (3.610 \bullet hs - 0.922 \bullet hs^2) \qquad (5b)$$

After developing equations for ground-to-limit volume ratios, their effectiveness was checked using an independent set of data. For each individual tree the difference between the observed values and the estimated values was calculated. Then for all trees of each species the mean absolute difference (bias) was computed. For the d/D expression the weighted average bias for softwoods is +0.011 and for hardwoods +0.018; for the h/H expression these are -0.002 and -0.001, respectively.

Finally the ratio equations developed here were compared with Honer's equations (Honer 1967, and Honer et al. 1983). Honer's two principal merchantable volume ratio equations for six softwood and three hardwood species were used in the comparisons: one as a function of $(d/D)^2$ and the other as a function of h/H. Both incorporate a variable stump height. These equations, together with their regression coefficients, were applied to the same independent data set which covers a variety of tree sizes, top diameters, and merchantable heights, and the results are summarized in Table 6. Comparison with the performances of equations presented in this report indicate that mean residuals are negligible using both methods and that there is almost no difference between the two approaches. Another comparison, using all nine species and studying behavior of individual observations revealed that there is no systematic error in either method. They both overestimate or underestimate.

If desired, taper equations can be derived from these merchantable volume ratio equations for estimates of d and h by equating the two VL/VT equations of each species and then solving for d and for h as outlined by Alemdag (1988). Accuracy will be less at both ends of the stem than in between. When developed, these taper equations will have the following forms:

$$d = D \bullet \left[\frac{c_1 \bullet (1 - h/H)^{c_2}}{b_1}\right]^{1/b_2} \qquad (6)$$

$$h = H \bullet \left[1 - \left(\frac{b_1 \bullet (d/D)^{b_2}}{c_1}\right)^{1/c_2}\right] \qquad (7)$$

These equations compare very well with the form-class taper curves developed earlier by the Canadian Forestry Service (Anon. 1930 and 1948) and later formulated by Alemdag (1983). For more precise estimates, the method developed by Newnham (1988) can be used.

* Please note that the previously suggested Model 6 for red pine and sugar maple (Alemdag 1988) is now replaced by Model 4.

APPLICATION OF THE CONVERSION FACTORS AND THE TAPER EQUATIONS

The application of these merchantable volume conversion factors is straightforward and simple. The following steps should be taken:

1. Decide on the merchantable top diameter (d) or merchantable height (h);
2. Measure breast height diameter (D) or total tree height (H), and the stump height (hs);
3. Calculate d/D or h/H, whichever is appropriate;
4. Use the appropriate formula for the species concerned, with the coefficients given in Table 4, for estimating the VL/VT ratio or K;
5. Calculate VS/VT ratio using average VS30/VT ratio from Table 5, and the p of measured hs;
6. Subtract VS/VT from VL/VT to find merchantable volume ratio (VM/VT) for this particular case (Items 4, 5, and 6 can be combined into one as illustrated in Equations 5a and 5b);
7. Multiply this merchantable volume conversion factor by the total stem volume (VT) to arrive at merchantable volume. Note that VT could be eight in metric or imperial measure and could also be expressed as a formula.

An example of this procedure is found in Table 7, using white spruce, once for d/D = 0.35 and once for h/H = 0.60. In this case, 0.35 means, for instance, 7 cm/20 cm, 8 cm/22.9 cm, 9 cm/25.7 cm, and 0.60 means, for instance, 12 m/20 m, 16 m/26.67 m, 18 m/30 m.

It should be noted that the merchantable equations presented in this report can also be used:

(a) with stand averages;
(b) for studying the volume distribution within a stem at various heights or at various stem diameters; and,
(c) for estimating the volume of a segment of a stem between two given heights or between two given stem diameters.

Using taper equations for estimating d requires the knowledge of D, H and h, and for estimating h, the knowledge of D, H and d. For instance for a white spruce with D = 22.0 cm and H = 18.60 m, diameter at 15.00 m above ground is 7.6 cm, and height along the stem to correspond a diameter of 12.5 cm is 11.06 m.

Although these findings are applicable to conditions similar to those in Ontario for any particular species, a test of their adequacy is recommended beforehand. These formulas can easily be incorporated with the calculation programs of an electronic field data collector.

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Table 1. List of the species studied.

Common name	Latin name
Softwoods	
Cedar, eastern red	*Juniperus virginiana* L.
Cedar, eastern white	*Thuja occidentalis* L.
Fir, balsam	*Abies balsamea* (L.) Mill.
Hemlock, eastern	*Tsuga canadensis* (L.) Carr.
Pine, eastern white	*Pinus strobus* L.
Pine, jack	*Pinus banksiana* Lamb.
Pine, red	*Pinus resinosa* Ait.
Spruce, black	*Picea mariana* (Mill.) B.S.P.
Spruce, white	*Picea glauca* (Moench) Voss
Tamarack	*Larix laricina* (Du Roi) K. Koch
Hardwoods	
Ash, black	*Fraxinus nigra* Marsh.
Ash, red	*Fraxinus pennsylvanica* Marsh.
Ash, white	*Fraxinus americana* L.
Aspen, largetooth	*Populus grandidentata* Michx.
Aspen, trembling	*Populus tremuloides* Michx.
Basswood	*Tilia americana* L.
Beech, American	*Fagus grandifolia* Ehrh.
Birch, white	*Betula papyrifera* Marsh.
Birch, yellow	*Betula alleghaniensis* Britton
Cherry, black	*Prunus serotina* Ehrh.
Elm, white	*Ulmus americana* L.
Hickory	*Carya spp.*
Maple, red	*Acer rubrum* L.
Maple, silver	*Acer saccharinum* L.
Maple, sugar	*Acer saccharum* Marsh.
Oak, red	*Quercus rubra* L.
Oak, white	*Quercus alba* L.
Poplar, balsam	*Populus balsamifera* L.

Table 2. Summary of observations.

Species	N*	n*	D (cm)		H (m)		d/D		h/H		VL/VT	
			Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Softwoods												
Cedar, eastern red	16	41	18.2	10.8-38.2	9.14	6.30-12.75	0.696	0.230-0.964	0.384	0.127-0.735	0.711	0.318-0.995
Cedar, eastern white	67	171	22.6	10.2-38.8	13.08	8.30-19.00	0.624	0.198-0.972	0.458	0.102-0.850	0.744	0.239-0.992
Fir, balsam	46	117	15.3	10.0-27.4	14.65	8.00-19.20	0.744	0.292-0.957	0.381	0.081-0.781	0.628	0.186-0.979
Hemlock, eastern	124	316	29.3	10.2-51.4	16.52	5.17-26.50	0.583	0.117-0.908	0.500	0.111-0 901	0.760	0.278-0.998
Pine, eastern white	130	334	34.7	9.9-68.7	21.38	5.40-38.50	0.575	0.114-0.931	0.538	0.103-0.956	0.769	0.235-0.999
Pine, jack	70	186	16.6	10.2-26.8	17.83	11.90-23.50	0.699	0.317-0.935	0.431	0.098-0.847	0.667	0.206-0.986
Pine, red	102	266	29.3	10.3-55.1	18.66	7.10-34.35	0.590	0.147-0.936	0.517	0.098-0.931	0.753	0.229-0.999
Spruce, black	42	108	13.6	10.0-22.2	13.59	9.10-18.90	0.767	0.360-0.945	0.357	0.079-0.772	0.598	0.173-0.977
Spruce, white	58	149	16.6	10.4-35.8	13.77	6.20-23.20	0.715	0.229-0.936	0.414	0.096-0.862	0.668	0.217-0.993
Tamarack	60	156	20.9	10.3-33.8	19.87	11.05-26.70	0.655	0.219-0.903	0.458	0.108-0.841	0.722	0.241-0.993
All softwoods	715	1844	24.6	9-9-68.7	17.13	5.17-38.50	0.638	0.117-0.972	0.470	0.079-0.956	0.720	0.173-0.999
Hardwoods												
Ash, black	18	42	17.2	10.1-33.1	15.01	9.15-20.30	0.702	0.218-0.932	0.397	0.102-0.775	0.681	0.265-0.991
Ash, red	20	57	22.8	12.0-40.2	19.34	13.50-26.70	0.598	0.206-0.867	0.450	0.132-0.828	0.727	0.304-0.993
Ash, white	63	162	26.3	10.7-53.7	18.89	11.75-26.93	0.567	0.151-0.895	0.455	0.138-0.837	0.764	0.323-0.996
Aspen, largetooth	71	180	19.2	9.6-39.2	19.68	11.60-28.90	0.661	0.207-0.927	0.430	0.066-0.849	0.687	0.143-0.996
Aspen, trembling	163	419	19.5	10.1-43.5	19.58	9.58-27.25	0.683	0.182-0.941	0.433	0.085-0.852	0.680	0.188-0.999
Basswood	68	173	30.3	11.5-54.8	19.38	9.41-26.10	0.582	0.141-0.913	0.476	0.121-0.852	0.761	0.270-0.998
Beech, American	70	182	27.8	10.5-46.3	19.77	9.72-26.50	0.615	0.184-0.955	0.468	0.106-0.858	0.759	0.254-0.995
Birch, white	100	258	19.5	10.1-32.7	18.29	11.70-22.25	0.666	0.232-0.951	0.430	0.071-0.797	0.711	0.208-0.989
Birch, yellow	88	228	37.3	10.4-70.3	20.49	10.00-25.60	0.556	0.124-0.934	0.468	0.088-0.874	0.781	0.255-0.998
Cherry, black	63	161	26.1	9.5-49.6	18.59	8.35-25.92	0.577	0.159-0.936	0.468	0.087-0.850	0.762	0.190-0.996
Elm, white	65	174	22.8	11.3-55.2	14.61	7.96-23.24	0.592	0.180-0.935	0.398	0.083-0.824	0.743	0.286-0.998
Hickory	65	172	23.5	10.0-46.6	21.21	11.60-29.40	0.585	0.185-0.907	0.430	0.076-0.821	0.733	0.222-0.992
Maple, red	37	97	27.8	13.5-45.2	20.04	10.76-25.35	0.574	0.185-0.896	0.453	0.152-0.796	0.771	0.396-0.994
Maple, silver	31	80	27.3	13.3-45.3	21.96	14.15-26.38	0.578	0.172-0.899	0.441	0.106-0.812	0.770	0.353-0.994
Maple sugar	93	238	31.1	10.0-57.8	19.75	9.86-26.41	0.596	0.133-0.925	0.448	0.076-0.838	0.750	0.203-0.997
Oak, red	135	324	25.5	10.1-55.3	17.18	9.92-23.00	0.585	0.171-0.926	0.477	0.106-0.889	0.777	0.255-0.997
Oak, white	49	126	28.2	9.9-74.3	12.99	5.00-21.50	0.577	0.119-0.945	0.424	0.125-0.803	0.761	0.283-0.996
Poplar, balsam	86	219	25.6	10.0-53.2	18.87	8.70-27.00	0.584	0.136-0.912	0.460	0.121-0.884	0.748	0.283-0.998
All hardwoods	1285	3292	25.4	9.5-74.3	18.77	5.00-29.40	0.608	0.119-0.955	0.446	0.066-0.889	0.741	0.143-0.999

Table 3. Conditioned models tested for ratios of ground-to-limit volume.

Model No.	Model form
	Using d/D as a variable
1	$K = 1 + b_1 \bullet (d/D)^{b_2}$
2	$K = 1 + b_1 \bullet (\ln(d/D + 1))^{b_2}$
3	$K = \exp(b_1 \bullet (d/D)^{b_2})$
	Using h/H as a variable
4	$K = 1 + c_1 \bullet (1 - h/H)^{c_2}$
5	$K = 1 + c_1 \bullet (0.693147 - \ln(h/H + 1))^{c_2}$
6	$K = \exp(c_1 \bullet (1 - h/H)^{c_2})$

K = VL/ VT

Table 4. Regression coefficients and statistics of the species for the adopted models as a function of d/D (Model 1) and of h/H (Model 4).

Species	Model No. 1				Model No. 4			
	b_1	b_2	FI	SEE%	c_1	c_2	FI	SEE%
Softwoods								
Cedar, eastern red	-0.66136	2.909	0.905	8.72	-1.15595	3.365	0.872	10.10
Cedar, eastern white	-0.81648	3.159	0.951	5.90	-0.98263	2.664	0.963	5.17
Fir, balsam	-0.86347	3.404	0.957	7.21	-1.01939	2.366	0.982	4.66
Hemlock, eastern	-0.65424	2.724	0.781	12.54	-1.16050	2.846	0.965	5.01
Pine, eastern white	-0.83899	3.284	0.888	8.93	-1.12164	2.587	0.979	3.86
Pine, jack	-1.04369	3.831	0.933	8.37	-1.01570	2.262	0.986	3.78
Pine, red	-0.92826	3.348	0.907	8.36	-1.12875	2.559	0.967	5.01
Spruce, black	-0.93210	3.711	0.910	10.78	-1.01964	2.343	0.981	4.95
Spruce, white	-0.87185	3.535	0.943	7.65	-0.99657	2.363	0.982	4.28
Tamarack	-0.85188	3.364	0.881	9.91	-1.05346	2.578	0.957	5.99
All softwoods	-0.80382	3.159	0.894	9.66	-1.08457	2.597	0.964	5.62
Hardwoods								
Ash, black	-0.66590	2.823	0.758	16.13	-1.06067	2.823	0.956	6.86
Ash, red	-1.13077	3.430	0.869	10.77	-1.19828	2.976	0.969	5.25
Ash, white	-0.85795	2.898	0.764	12.21	-1.07355	3.057	0.932	6.56
Aspen, largetooth	-1.01248	3.510	0.941	7.90	-1.13992	2.706	0.985	3.97
Aspen, trembling	-0.90924	3.475	0.930	8.58	-1.11695	2.687	0.983	4.28
Basswood	-0.75815	2.822	0.876	9.20	-1.17853	3.042	0.956	5.47
Beech, American	-0.70626	2.982	0.848	10.36	-1.05299	2.900	0.956	5.59
Birch, white	-0.86363	3.387	0.927	8.05	-1.05008	2.728	0.976	4.61
Birch, yellow	-0.76194	2.914	0.859	9.45	-1.09292	3.319	0.953	5.48
Cherry, black	-0.90094	3.152	0.783	12.48	-1.09331	3.005	0.954	5.75
Elm, white	-0.97656	3.111	0.750	12.89	-0.93001	3.110	0.927	6.95
Hickory	-1.03149	3.155	0.773	13.63	-1.00293	2.898	0.945	6.69
Maple, red	-0.78771	2.814	0.924	6.91	-1.05371	3.092	0.975	3.99
Maple, silver	-0.82344	2.943	0.865	8.99	-1.00476	3.113	0.954	5.26
Maple, sugar	-0.72968	2.840	0.847	11.09	-1.24846	3.425	0.954	6.09
Oak, red	-0.74310	2.926	0.797	11.14	-1.03191	2.900	0.942	5.93
Oak, white	-0.72134	2.551	0.756	12.62	-0.95672	3.122	0.873	9.10
Poplar, balsam	-1.06239	3.363	0.795	11.91	-1.11369	2.941	0.969	4.65
All hardwoods	-0.81861	3.009	0.840	11.13	-1.08301	2.978	0.945	6.53

Table 5. Mean stump volume ratios (VS30/VT) at 0.30 m stump height.

Softwoods	VS30/VT	Hardwoods	VS30/VT
Cedar, eastern red	0.0517	Ash, black	0.0577
Cedar, eastern white	0.0634	Ash, red	0.0607
Fir, balsam	0.0581	Ash, white	0.0541
Hemlock, eastern	0.0596	Aspen, largetooth	0.0409
Pine, eastern white	0.0485	Aspen, trembling	0.0438
Pine, jack	0.0446	Basswood	0.0477
Pine, red	0.0476	Beech, American	0.0557
Spruce, black	0.0603	Birch, white	0.0585
Spruce, white	0.0596	Birch, yellow	0.0688
Tamarack	0.0529	Cherry, black	0.0556
All softwoods	0.0539	Elm, white	0.0574
		Hickory	0.0519
		Maple, red	0.0570
		Maple, silver	0.0704
		Maple, sugar	0.0554
		Oak, red	0.0673
		Oak, white	0.0534
		Poplar, balsam	0.0543
		All hardwoods	0.0552

Table 6. Results of the merchantable volume ratio comparison with Honer's expressions (with hs = 0.30 m).

Species	Number of observations	Mean difference (bias)*			
		d/D expression		h/H expression	
		Honer's	Alemdag's	Honer's	Alemdags
Fir, balsam	19	0.017	0.010	-0.002	-0.004
Pine, eastern white	55	-0.026	-0.004	-0.014	-0.004
Pine, jack	30	-0.006	-0.004	-0.076	0.004
Pine, red	44	0.019	0.019	-0.019	-0.001
Spruce, black	17	-0.024	-0.009	-0.005	0.000
Spruce, white	24	-0.024	0.015	-0.009	-0.004
Birch, white	42	-0.045	0.011	-0.018	-0.002
Birch, yellow	37	-0.047	0.004	-0.024	0.000
Poplar, balsam	36	0.071	0.029	-0.044	-0.001
Weighted averages		-0.008	0.008	-0.025	-0.001

* Difference = estimated-observed

Table 7. An example of the estimated volume ratios of different stem components by various stump heights using Models 1 and 4 for white spruce.

d/D	h/H	Stump height (m)	Ground-to-limit volume	Top volume as ratio	Stump volume of total	Merch. volume stem volume	Total volume*
0.35		0.10	0.9787	0.0213	0.0210	0.9577	1.0
		0.20	0.9787	0.0213	0.0408	0.9379	1.0
		0.30	0.9787	0.0213	0.0596	0.9191	1.0
		0.40	0.9787	0.0213	0.0773	0.9014	1.0
	0.60	0.10	0.8857	0.1143	0.0210	0.8647	1.0
		0.20	0.8857	0.1143	0.0408	0.8449	1.0
		0.30	0.8857	0.1143	0.0596	0.8261	1.0
		0.40	0.8857	0.1143	0.0773	0.8084	1.0

* Either ground-to-limit volume plus top volume, or, stump volume plus merchantable volume plus top volume.

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