BIOMASS EQUATIONS FOR TEN MAJOR TREE SPECIES OF THE PRAIRIE PROVINCES

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ABSTRACT

Ten major tree species of the prairie provinces were sampled for aboveground biomass in 1979 and 1980 in order to develop regional biomass equations. Measurements were taken of diameter, height, crown length and width, age, and the biomass weights of subsamples obtained from tree stem and non-stem components. Ovendry weights for the subsamples were determined in the laboratory and were used to calculate the dry/fresh weight ratios and bark/wood weight ratios for the sampled tree components. Five variables based on diameter and height measurements (D, H, D^2H, D^2, and D^3) were tested in all combinations as predictors for biomass. A multiple regression model using all five variables provided the best estimates. A polynomial model based on D, D^2, and D^3 and a model based on only D^2H were nearly as good. Equations derived from the three models are presented for each of the 10 tree species.

RESUME

En 1979 et 1980, on a échantillonné dix essences d'arbres importantes des Prairies pour déterminer la biomasse au-dessus du sol afin d'établir des équations régionales de la biomasse. On a mesuré le diamètre, la hauteur ainsi que la longueur et la largeur du houppier des arbres, et on a déterminé leur âge ainsi que le poids de la biomasse de sous-échantillons prélevés sur les tiges et sur d'autres parties des arbres. Au laboratoire, on a séché à l'étuve et pesé les sous-échantillons pour calculer les rapports du poids sec au poids frais ainsi que du poids de l'écorce au poids du bois. On a vérifié dans toutes leurs combinaisons possibles 5 variables (D, H, D^2H, D^2, et D^3) où entraient la mesure de diamètre et de la hauteur et qui permettraient de calculer la biomasse. On a obtenu les meilleurs résultats avec un modèle à régression multiple utilisant les 5 variables. Un modèle à polynômes utilisant D, D^2, et D^3 et un modèle où entrait seulement D^2H ont été presque aussi bons. Pour chacune des 10 essences, on présente les équations établies à l'aide de ces trois modèles.

CONTENTS

FIGURES

TABLES

INTRODUCTION

The rapid increase in the price of oil since 1973 has provided an impetus for research to explore and develop alternative sources of energy. It has also served to focus attention on the inevitable depletion of the world's nonrenewable resources if the industrialized nations continue to consume these resources for energy production at the current rates. Canada, in spite of some still untapped fossil fuel energy supplies, is no exception.

Many recent reports (Department of Energy, Mines, and Resources 1976; Evans 1974; Karchesy and Koch 1979; McCarthy 1979; Nautiyal 1979; Purschwitz 1979; Sampson 1979) have considered the potential of biomass for augmenting the energy production requirements. Forest biomass consists of all tree and shrub materials from root tips to leaf or needle tips. Biomass is gaining recognition as a potentially viable renewable resource offering at least a partial solution to the existing energy problems on the North American continent (Wellwood 1979). The cultivation of forest crops is gaining support as a relatively efficient way of capturing and storing solar energy (McCarthy 1979).

Gathering quantitative information on the availability of forest biomass on a sustained basis is a prerequisite to the future use of this resource. At present only very limited data are available for reliably estimating the existing forest biomass in the prairie provinces. The great diversity of vegetation covering widely different sites over a vast geographical area makes such estimations exceedingly difficult. For example, poplars have the widest range and largest volume of any hardwoods in Canada, occupying sites with quite different growth rates (Maini and Cayford 1968). Poplars also are the fastest growing species on many sites in the prairies and, along with other tree species, present attractive possibilities for future use as a source of energy from forest lands.

Much information is already available in the regional forest inventories on the merchantable volume of the growing stock, at least for important species. Such inventories are constantly being updated and expanded through modern techniques. By collecting additional information on relatively few parameters, it is possible to incorporate biomass estimates into timber inventories. Prediction equations for regional application can thus be derived, based on the regional forest volume inventories and biomass weight data sampled in the field.

The objective of this study was to develop regional biomass equations that eventually could be used to convert a conventional forest inventory to a biomass inventory.

METHODS

The study was conducted in Alberta, Saskatchewan, and Manitoba during the summers of 1979 and 1980. Sixty trees of each of the following species were sampled:

Softwoods

- Jack pine (*Pinus banksiana* Lamb.)
- Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.)
- White spruce (*Picea glauca* (Moench) Voss)
- Black spruce (*Picea mariana* (Mill.) BSP)
- Balsam fir (*Abies balsamea* (L.) Mill.)
- Alpine fir (*Abies lasiocarpa* (Hook.) Nutt.)
- Larch (*Larix laricina* (Du Roi) K. Koch)

Hardwoods

- Trembling aspen (*Populus tremuloides* Michx.)
- White birch (*Betula papyrifera* Marsh.)
- Balsam poplar (*Populus balsamifera* L.)

In each province, five trees for each of eight species were sampled by diameter classes of 0-10, 11-20, 21-30, and 31+ cm. Lodgepole pine and alpine fir were sampled only along a north-south gradient in Alberta, with 15 trees in each diameter class.

FIELD PROCEDURES

The following field information was recorded for each tree:

1. tree identification number,
2. species,
3. location (latitude, longitude),
4. diameter at breast height outside bark (dbh) at 1.3 m,
5. total height,
6. crown width,
7. crown length,
8. stump age,
9. height to 10-cm diameter outside bark (dob) top,
10. height to 2-cm dob top, and
11. diameter outside bark at base of live crown.

Field data on stem and nonstem components were obtained according to procedures outlined by Young (1979, 1980).

The tree was limbed, and all branches were sorted into piles of live and dead branches on a plastic sheet or tarp. Live branches were further separated into two subcategories: (1) small branches (SB)—branches and foliage less than 2 cm dob, and (2) large branches (LB)—branches 2 cm and greater dob. Total fresh weight was obtained for each of the three categories. Three subsamples were taken from each category, and the fresh weights were measured to the nearest 0.1 g.

On the felled and limbed tree stem, marks were made to indicate where the bole was 10 and 2 cm dob and, depending on stem size, a number of further measurements were obtained (Figs. 1 and 2). On merchantable stems, four equidistant points between the cut end and the 10-cm dob mark were located, flagged, and measured for diameter outside bark and height, or length, of each section. These were labeled MS1, MS2, MS3, and MS4.

On nonmerchantable stems, three equidistant points between the 10- and 2-cm dob marks were similarly located, flagged, and measured for their heights and diameters. These were labeled NM1, NM2, and NM3. For the section from 2 cm dob to the tip of the tree stem, the midpoint (T1) was located and flagged, and the diameter and height were determined.

The tree stem was cut and weighed for the total fresh weight of the merchantable stem, nonmerchantable stem, and stump (ground level to stump height of 0.15 m). Subsamples 1.0 cm thick were taken at each flagged location, and the disks so obtained were sealed immediately in plastic bags. Fresh weight to the nearest 0.1 g was determined within 24 hours. Disk subsamples of up to 1 cm thickness were similarly taken at the marks for breast height (MBH) and stump height (SH). A small subsample of approximately 30 g was obtained from coniferous trees for cone moisture determination.

Alemdag (1980) and Newbould (1967) provide detailed descriptions of the methods and procedures commonly used for the data collection and development of forest biomass relationships.

LABORATORY PROCEDURES

All disk subsamples (SH, MBH, MS1, MS2, MS3, MS4, NM1, NM2, NM3, T1) and the live large (2 cm and greater dob) branch subsamples (LB1, LB2, LB3) were debarked. The wood and bark from each subsample were oven-dried at 103 ± 2°C for 24 hours or until a constant weight was obtained. The ovendry weight was measured to the nearest 0.1 g.

The live small branch plus foliage subsamples less than 2 cm dob (SB1, SB2, SB3) were not debarked and were oven-dried at the same temperature to a constant weight. The dead branch subsamples (DB1, DB2, DB3) were also similarly oven-dried. Both sets of samples were weighed to the nearest 0.1 g.

COMPUTER PROGRAMMING AND PROCEDURES FOR BASIC COMPUTATIONS

Computer programs in FORTRAN were written for obtaining biomass information on individual trees from the field and laboratory subsampling data[1]. The basic step involved in these computations was the deri-

[1] These computer programs were developed for the PDP 11/60 minicomputer by Nadine Leenders and Chi Martin of the Northern Forest Research Centre and are available on request.

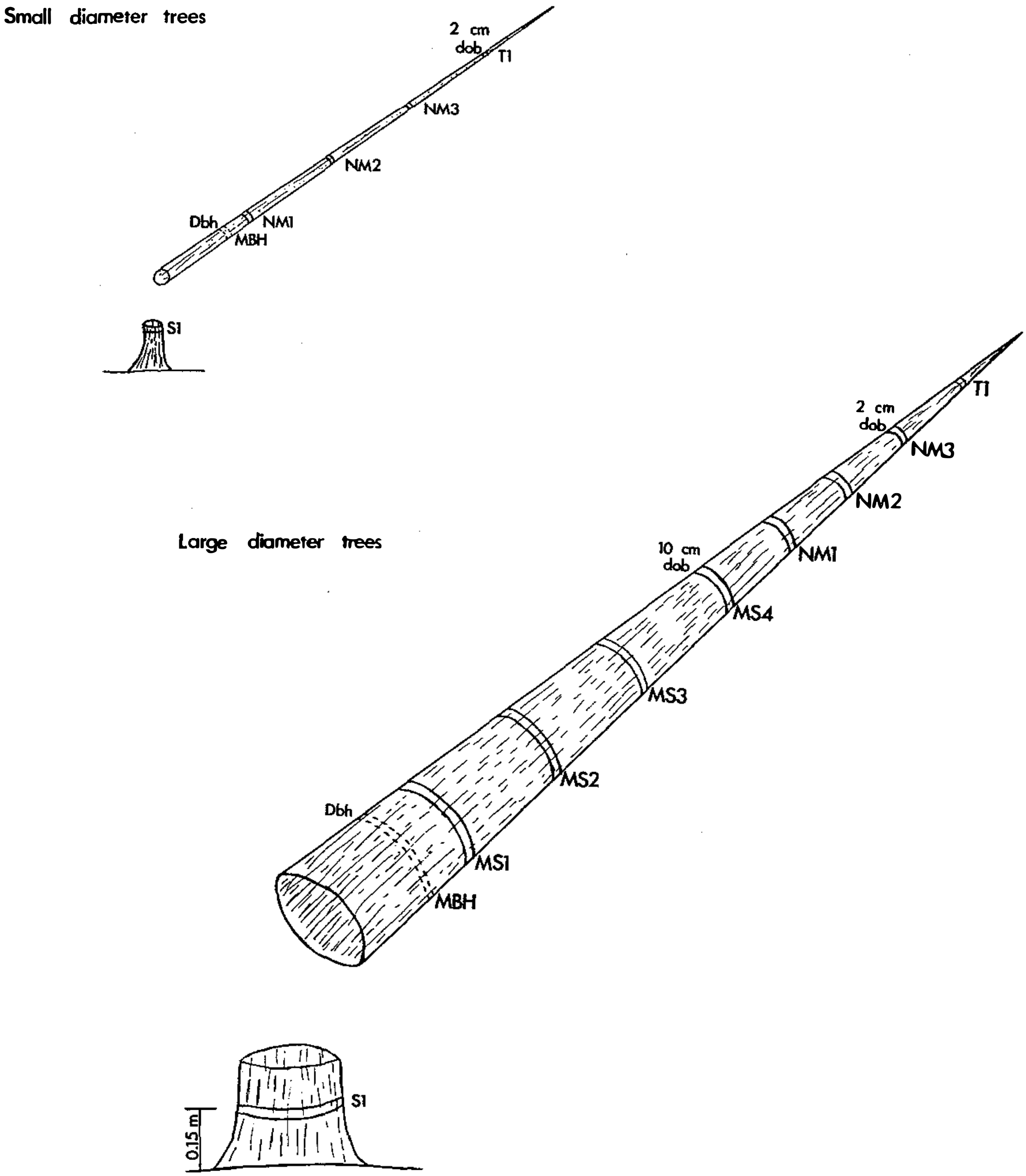

Figure 1. Locations of stem subsamples taken from the merchantable and nonmerchantable trees.

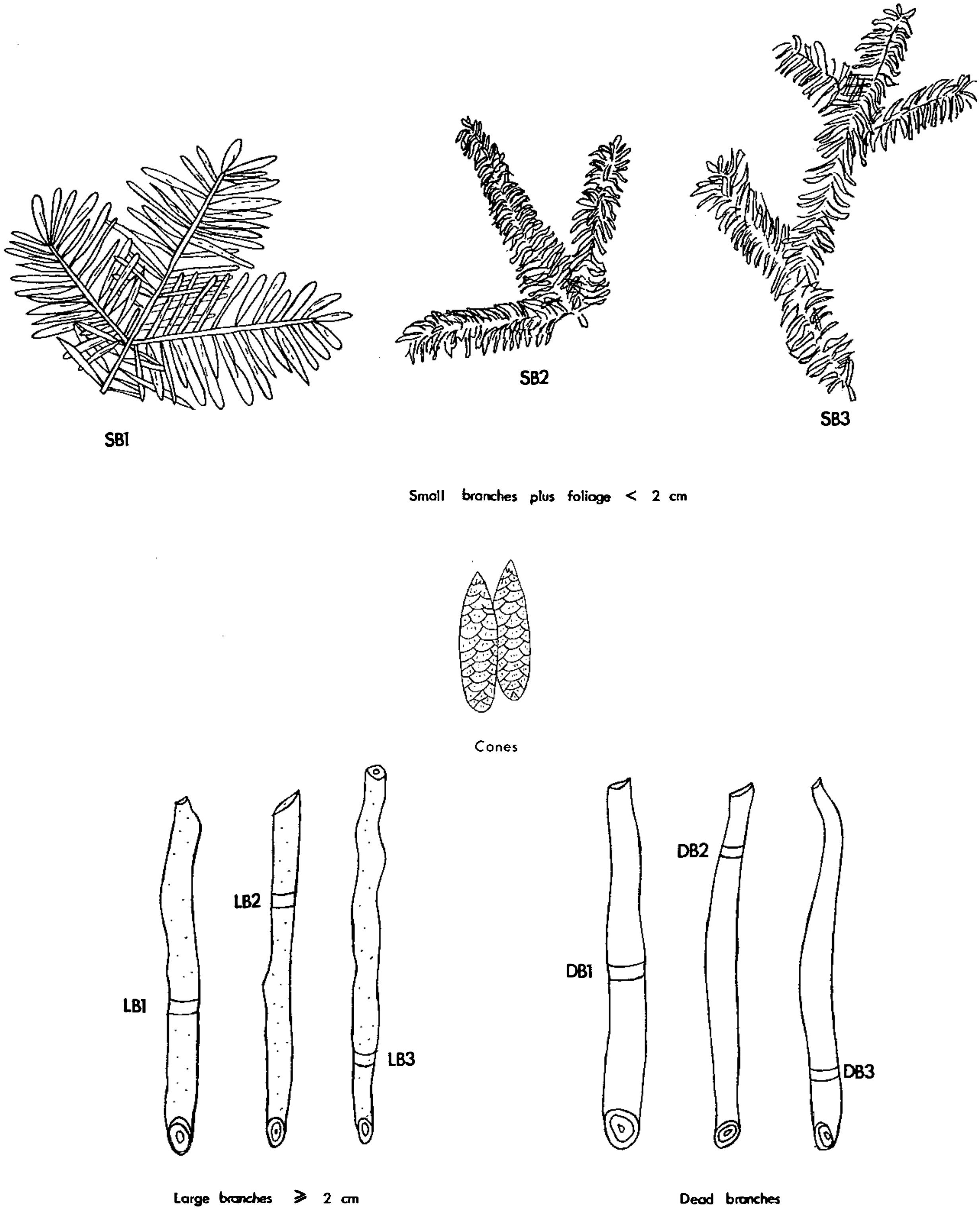

Figure 2. Locations of nonstem subsamples taken from the tree canopy.

vation of volume-weighted dry/fresh weight ratios (R_i) and volume-weighted bark/wood dry weight ratios (r_i) for the disk subsamples: SH, MBH, MS1, MS2, MS3, and MS4 for the merchantable stem; NM1, NM2, NM3, and T1 for the nonmerchantable stem; and LB1, LB2, and LB3 for the large live branches. Only the dry/fresh weight ratio computations were done for the subsamples SB1, SB2, and SB3 for the small live branches and foliage; DB1, DB2, and DB3 for the dead branches; and the cone subsample obtained from the coniferous trees.

The above-mentioned ratios were weighted on a volume basis to obtain improved estimates. The following equation was used to compute the volume (V) of the stem segments from which the disk subsamples had been obtained:

$$V_i = \frac{\pi}{8}(DOB^2{}_{i+1} + DOB^2{}_i)(H_{i+1} - H_i)$$

DOB_{i+1} is the diameter outside bark at the smaller end and DOB_i is the diameter outside bark for the larger end for each stem section. H_{i+1} and H_i are the heights of the tree at each of these ends, respectively. Total volume of the tree stem is obtained from the sum of the components $V = \Sigma V_i$.

The ratios R_i and r_i for each subsample disk were determined as follows:

$$R_i = \frac{\text{Dry weight of wood + Dry weight of bark}}{\text{Fresh weight}}$$

$$r_i = \frac{\text{Dry weight of bark}}{\text{Dry weight of wood + Dry weight of bark}}$$

The weighted ratios R'_i and r'_i for the tree stem components were obtained as follows:

$$R'_i = \frac{\Sigma_i(\frac{R_{i+1} + R_i}{2} V_i)}{V}$$

$$r'_i = \frac{\Sigma_i(\frac{r_{i+1} + r_i}{2} V_i)}{V}$$

The weighted ratios R'_i and r'_i were used to determine the dry biomass weight of an entire tree component (DW) and its partition into dry weight of bark (DWB) and dry weight of wood (DWW):

$$DW = R'_i \text{ (Fresh weight of tree component)}$$

$$DWB = r'_i \text{ (DW)}$$

For large branch subsamples, the ratios R_i and r_i were obtained and their averages were used (instead of weighting by volume) to obtain the dry bark and dry wood biomass weights. For small branches, the average R_i was used to compute the dry biomass weight, without further partitioning into the bark and wood subcomponents. The biomass dry weights were similarly derived for the dead branches and for cones. All tree components (with the exception of dead branches, cones, and foliage on branches <2 cm dob) were summed to provide the dry biomass weights for the entire tree above ground.

DERIVATION OF BIOMASS PREDICTION EQUATIONS

Preliminary regression analyses were performed on five predictor variables based on diameter at breast height (D) and total tree height (H): D, H, D^2H, D^2, and D^3. These analyses showed that in most cases the most important predictor for the various tree components was D^2, followed by D^3 and D.

Since diameter is the most readily available information (all timber inventories contain measurements of diameter at breast height), it was decided to extract the fullest possible prediction of biomass weight (W) from the linear, quadratic, and cubic terms of this variable. A third-degree polynomial of the form

[Model 1]

$$W_i = a_0 + a_1 D + a_2 D^2 + a_3 D^3$$

was therefore tested and recommended for use when only dbh measurements are available. The model parameters a_0, a_1, a_2, and a_3 are the regression coefficients estimated from the biomass data.

If the tree height data are also available, a model of the form

[Model 2]

$$W_2 = a_0 + a_1 D + a_2 H + a_3 D^2 H + a_4 D^2 + a_5 D^3$$

can be selected to provide a better fit.

As both of the above-mentioned models use linear combinations of predictors and avoid logarithmic or other nonlinear scale transformations, each model has the advantage of being additive and unbiased. A third model, commonly used for volume determination and of the form

[Model 3]

$$W_3 = a_0 + a_1 D^2 H$$

was also used to assist in the development and assessment of local biomass prediction and variation in the height-diameter relationships. The use of measures of tree size such as diameter and height has also the generally accepted advantage of reflecting the accumulated history of growth (Madgwick and Kreh 1980) compared to measures based on canopy components, which are more affected by the current growth and environment.

Regression analyses for the models were done through specially written computer programs[2]. In addition to providing statistical information on the model coefficients, these programs have a built-in feature allowing derivation of confidence bands for the multiple regression cases dealing with three predictor variables (Model 1) and five predictor variables (Model 2). The numerical data for the upper and lower limits (for the individual and for the mean biomass weights in either case) were computed and used to plot[3] the confidence bands for the entire living tree above ground at a 95% confidence level.

RESULTS

The dry/fresh weight ratios for the disk subsamples SH, MBH, MS1, MS2, MS3, MS4, NM1, NM2, NM3, and T1 were summarized for the 10 prairie tree species to provide a listing of statistical characteristics such as mean, standard deviation, range, and coefficient of variation[4]. As expected, the ratios show a general decline upward along the tree stem, thus confirming that there is greater moisture content in the more recent growth and less in the heartwood in relation to softwood along the stem. The average dry/fresh weight ratios for each species on the basis of the 10 stem components were balsam fir 0.433, white spruce 0.473, black spruce 0.552, jack pine 0.525, trembling aspen 0.548, alpine fir 0.475, lodgepole pine 0.501, tamarack larch 0.469, balsam poplar 0.496, and white birch 0.521. The overall average ratio for all the sampled tree species was 0.499.

The statistical characteristics of the bark/wood dry weight ratios of the 10 species for the 10 stem components were similarly summarized[5]. In general, for all species the mean ratios are usually lowest at MS1 ($\geqslant 0.1$) and increase in both directions, attaining their highest values near the stem tip ($\geqslant 0.4$).

Biomass prediction equations based on the three models are presented in Tables 1-10 for each tree species. The tables include each stem and nonstem component's mean biomass weight, standard deviation, R^2, standard error of estimate, and the number of samples used in the derivation of the equations.

A bar diagram (Fig. 3) depicting the fresh and dry weights of biomass for the sampled tree species provides a visual comparison of the weight loss that occurs in various tree species when dried to a constant weight from

[2] These computer programs were developed by Douglas Whitfield and are available from the Northern Forest Research Centre.

[3] This computer plotting program was developed by Nadine Leenders of the Northern Forest Research Centre and is available upon request.

[4, 5] These are on file and are available from the author.

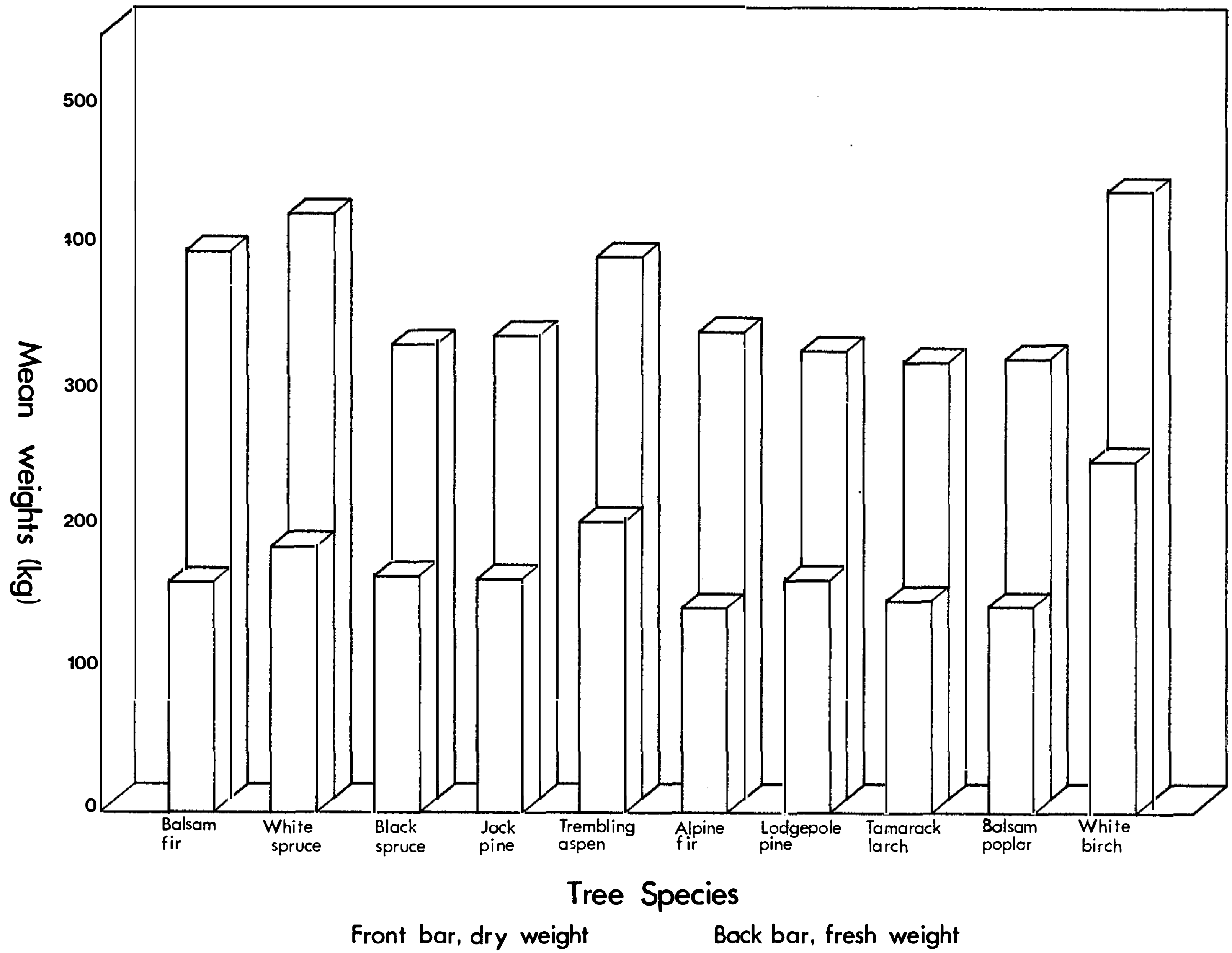

Figure 3. Fresh and dry weight biomass of the 10 tree species.

Table 1. Equations for predicting biomass (kg) of balsam fir

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	5.65	5.73	$W_1 = -0.84760 + 0.29542D - 0.01380D^2 + 0.00051D^3$	0.90	1.86	60
				$W_2 = -1.03666 + 0.29744D + 0.03057H - 0.00023D^2H - 0.01356D^2 + 0.00063D^3$	0.91	1.84	
				$W_3 = 0.53738 + 0.00048D^2H$	0.84	2.33	
	Bark	0.89	0.92	$W_1 = -0.15156 + 0.05634D - 0.00306D^2 + 0.00010D^3$	0.90	0.29	
				$W_2 = -0.18168 + 0.05941D + 0.00319H - 0.00003D^2H - 0.00313D^2 + 0.00012D^3$	0.91	0.29	
				$W_3 = 0.06883 + 0.00008D^2H$	0.84	0.37	
Stem ≥10 cm	Wood	106.03	111.69	$W_1 = -4.43189 - 0.32921D + 0.14775D^2 + 0.00260D^3$	0.93	30.11	47
				$W_2 = 8.90086 - 2.55605D - 0.87876H + 0.01322D^2H + 0.21669D^2 - 0.00593D^3$	0.99	13.20	
				$W_3 = -1.89075 + 0.01017D^2H$	0.98	15.23	
	Bark	17.30	19.59	$W_1 = -1.71278 + 0.33252D - 0.01294D^2 + 0.00125D^3$	0.92	5.69	
				$W_2 = 0.25193 + 0.05231D - 0.15887H + 0.00201D^2H - 0.00476D^2 - 0.00002D^3$	0.96	4.05	
				$W_3 = -1.40633 + 0.00176D^2H$	0.96	4.01	
Stem <10 ≥2 cm	Wood	5.17	2.55	$W_1 = -2.35534 + 1.59487D - 0.08198D^2 + 0.00119D^3$	0.40	2.02	60
				$W_2 = -2.36974 + 1.54120D + 0.03530H - 0.00009D^2H - 0.07975D^2 + 0.00121D^3$	0.41	2.05	
				$W_3 = 5.48751 - 0.00003D^2H$	0.02	2.55	
	Bark	1.09	0.44	$W_1 = -0.39021 + 0.25101D - 0.01142D^2 + 0.00016D^3$	0.46	0.33	
				$W_2 = -0.35769 + 0.23365D + 0.00517H + 0.00002D^2H - 0.01076D^2 + 0.00014D^3$	0.48	0.33	
				$W_3 = 0.99601 + 0.00001D^2H$	0.05	0.44	
Live branches ≥2 cm	Wood	8.07	13.37	$W_1 = 6.29080 - 1.74858D + 0.10223D^2 - 0.00108D^3$	0.57	9.01	60
				$W_2 = 2.89252 - 1.49769D + 0.41800H - 0.00378D^2H + 0.09773D^2 + 0.00115D^3$	0.86	5.22	
				$W_3 = -0.01783 + 0.00076D^2H$	0.38	10.58	
	Bark	2.80	4.72	$W_1 = 2.00809 - 0.55358D + 0.03165D^2 - 0.00030D^3$	0.56	3.20	
				$W_2 = 0.85589 - 0.46830D + 0.14160H - 0.00128D^2H + 0.03011D^2 + 0.00045D^3$	0.83	2.03	
				$W_3 = -0.06140 + 0.00027D^2H$	0.39	3.73	

Table 1 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	16.43	18.34	$W_1 = 6.60086 - 1.84881D + 0.14565D^2 - 0.00190D^3$	0.65	11.06	60
			$W_2 = 2.67711 - 1.60276D + 0.50937H - 0.00442D^2H + 0.14225D^2 + 0.00067D^3$	0.86	7.05	
			$W_3 = 4.22997 + 0.00115D^2H$	0.47	13.53	
Living tree above ground without foliage[2]	163.48	162.56	$W_1 = 6.419 - 2.519D + 0.3373D^2 + 0.0020D^3$	0.98	25.86	60
			$W_2 = 12.91 - 7.028D + 2.243H + 0.00336D^2H + 0.4692D^2 - 0.00157D^3$	0.98	23.02	
			$W_3 = 7.99821 + 0.01465D^2H$	0.96	31.95	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 2. Equations for predicting biomass (kg) of white spruce

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	5.61	5.58	$W_1 = -0.01874 + 0.04588D + 0.00377D^2 + 0.00016D^3$	0.98	0.84	60
				$W_2 = -0.09066 + 0.12803D - 0.07109H - 0.00005D^2H + 0.00400D^2 + 0.00016D^3$	0.98	0.84	
				$W_3 = 0.42003 + 0.00043D^2H$	0.96	1.08	
	Bark	0.68	0.63	$W_1 = 0.04249 - 0.00610D + 0.00172D^2 - 0.00001D^3$	0.84	0.26	
				$W_2 = 0.01382 + 0.02543D - 0.02681H - 0.00002D^2H + 0.00176D^2 - 0.00001D^3$	0.85	0.25	
				$W_3 = 0.14292 + 0.00004D^2H$	0.81	0.28	
Stem ⩾10 cm	Wood	134.31	142.73	$W_1 = 5.36016 - 3.26012D + 0.36508D^2 - 0.00025D^3$	0.98	20.55	46
				$W_2 = 1.21706 - 3.92214D + 2.63272H + 0.00821D^2H + 0.13148D^2 - 0.00014D^3$	0.99	15.33	
				$W_3 = -0.19070 + 0.01103D^2H$	0.99	15.17	
	Bark	15.51	16.40	$W_1 = 0.01449 - 0.21177D + 0.03349D^2 + 0.00009D^3$	0.97	2.84	
				$W_2 = -0.46285 - 0.21076D + 0.20694H + 0.00078D^2H + 0.01011D^2 + 0.00011D^3$	0.98	2.59	
				$W_3 = 0.15757 + 0.00126D^2H$	0.98	2.55	
Stem <10 ⩾2 cm	Wood	4.86	2.52	$W_1 = -4.31539 + 1.73267D - 0.07927D^2 + 0.00103D^3$	0.62	1.60	60
				$W_2 = -3.17164 + 0.91769D + 0.51750H - 0.00018D^2H - 0.06043D^2 + 0.00096D^3$	0.71	1.43	
				$W_3 = 5.00505 - 0.00001D^2H$	0.004	2.54	
	Bark	1.02	0.47	$W_1 = -0.62114 + 0.26519D - 0.01116D^2 + 0.00014D^3$	0.59	0.31	
				$W_2 = -0.39235 + 0.10292D + 0.10258H - 0.00004D^2H - 0.00736D^2 + 0.00013D^3$	0.69	0.27	
				$W_3 = 0.91776 + 0.00001D^2H$	0.05	0.46	
Live branches ⩾2 cm	Wood	8.89	14.85	$W_1 = 5.74703 - 1.57105D + 0.08764D^2 - 0.00076D^3$	0.60	9.65	60
				$W_2 = 3.10961 + 0.60984D - 1.56942H - 0.00021D^2H + 0.05800D^2 - 0.00059D^3$	0.64	9.32	
				$W_3 = -1.66831 + 0.00087D^2H$	0.56	9.91	
	Bark	2.68	4.66	$W_1 = 0.91887 - 0.22848D + 0.00938D^2 + 0.00008D^3$	0.67	2.76	
				$W_2 = 0.29357 + 0.29142D - 0.37563H - 0.00006D^2H + 0.00248D^2 + 0.00012D^3$	0.69	2.71	
				$W_3 = -0.80673 + 0.00029D^2H$	0.62	2.89	

Table 2 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	15.26	15.25	$W_1 = 0.51223 - 0.00578D + 0.02353D^2 + 0.00012D^3$	0.85	6.12	60
			$W_2 = -4.43410 + 3.06056D - 1.66658H + 0.00175D^2H - 0.07890D^2 + 0.00040D^3$	0.86	5.94	
			$W_3 = 2.05618 + 0.00108D^2H$	0.84	6.24	
Living tree above ground without foliage[2]	188.87	194.28	$W_1 = 7.69727 - 3.23895D + 0.43412D^2 + 0.00060D^3$	0.98	25.72	60
			$W_2 = -3.85515 + 1.00044D - 0.24810H + 0.01018D^2H + 0.06119D^2 + 0.00113D^3$	0.99	23.23	
			$W_3 = 6.09159 + 0.01499D^2H$	0.99	23.43	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 3. Equations for predicting biomass (kg) of black spruce

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	5.75	5.83	$W_1 = -0.64233 + 0.24194D - 0.01049D^2 + 0.00051D^3$	0.92	1.74	60
				$W_2 = 0.15578 - 0.15598D + 0.09071H - 0.00065D^2H + 0.01980D^2 + 0.00031D^3$	0.92	1.73	
				$W_3 = 0.08764 + 0.00058D^2H$	0.89	1.96	
	Bark	0.69	0.66	$W_1 = -0.12886 + 0.04826D - 0.00209D^2 + 0.00007D^3$	0.86	0.26	
				$W_2 = -0.05736 + 0.01889D + 0.00070H - 0.00007D^2H + 0.00100D^2 + 0.00004D^3$	0.86	0.26	
				$W_3 = 0.07846 + 0.00006D^2H$	0.83	0.27	
Stem ≥10 cm	Wood	117.02	117.27	$W_1 = 17.81047 - 7.56202D + 0.72172D^2 - 0.00741D^3$	0.98	18.61	47
				$W_2 = -2.02286 - 0.09863D + 0.61653H + 0.02125D^2H - 0.17606D^2 - 0.00088D^3$	0.99	11.77	
				$W_3 = -2.79907 + 0.01234D^2H$	0.99	13.46	
	Bark	12.65	12.52	$W_1 = -0.36818 - 0.19350D + 0.04115D^2 - 0.00021D^3$	0.94	3.21	
				$W_2 = -1.93792 + 0.34288D + 0.11310H + 0.00180D^2H - 0.03316D^2 + 0.00034D^3$	0.95	3.00	
				$W_3 = 0.12113 + 0.00129D^2H$	0.95	2.95	
Stem <10 ≥2 cm	Wood	7.32	4.15	$W_1 = -7.03615 + 2.82359D - 0.14691D^2 + 0.00226D^3$	0.38	3.35	60
				$W_2 = -6.25785 + 1.93001D + 0.68690H + 0.00043D^2H - 0.14765D^2 + 0.00238D^3$	0.44	3.25	
				$W_3 = 6.78664 + 0.00005D^2H$	0.02	4.15	
	Bark	1.63	0.91	$W_1 = -1.04748 + 0.43946D - 0.02009D^2 + 0.00029D^3$	0.36	0.75	
				$W_2 = -1.22094 + 0.46979D + 0.04676H + 0.00026D^2H - 0.03004D^2 + 0.00036D^3$	0.41	0.73	
				$W_3 = 1.34715 + 0.00003D^2H$	0.09	0.87	
Live branches ≥2 cm	Wood	6.52	13.42	$W_1 = -2.15959 + 0.87414D - 0.08934D^2 + 0.00258D^3$	0.61	8.59	60
				$W_2 = 3.82547 - 2.16219D + 0.74218H - 0.00477D^2H + 0.13463D^2 + 0.00111D^3$	0.65	8.32	
				$W_3 = -3.18798 + 0.00100D^2H$	0.49	9.62	
	Bark	1.77	3.40	$W_1 = -1.03019 + 0.35722D - 0.03189D^2 + 0.00083D^3$	0.71	1.89	
				$W_2 = 0.88085 - 0.63944D + 0.26913H - 0.00146D^2H + 0.03800D^2 + 0.00038D^3$	0.76	1.75	
				$W_3 = -0.84827 + 0.00027D^2H$	0.56	2.28	

Table 3 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	14.44	16.15	$W_1 = 0.36396 - 0.03142D + 0.02484D^2 + 0.00022D^3$	0.68	9.43	60
			$W_2 = 11.13965 - 5.06496D + 0.82347H - 0.00949D^2H + 0.45402D^2 - 0.00272D^3$	0.79	7.66	
			$W_3 = 1.20982 + 0.00136D^2H$	0.63	9.85	
Living tree above ground without foliage[2]	167.82	161.55	$W_1 = 5.81313 - 2.99915D + 0.48658D^2 - 0.00086D^3$	0.99	20.27	60
			$W_2 = 4.56422 - 5.36233D + 3.39266H + 0.00729D^2H + 0.26043D^2 + 0.00133D^3$	0.99	18.94	
			$W_3 = 2.84963 + 0.01699D^2H$	0.99	19.26	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 4. Equations for predicting biomass (kg) of jack pine

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	5.43	4.95	$W_1 = 0.84173 - 0.18941D + 0.02056D^2 - 0.00012D^3$	0.94	1.27	60
				$W_2 = 0.47011 + 0.03528D - 0.06273H + 0.00046D^2H + 0.00364D^2 - 0.00007D^3$	0.95	1.17	
				$W_3 = 0.44305 + 0.00051D^2H$	0.95	1.15	
	Bark	0.79	0.69	$W_1 = 0.24265 - 0.06113D + 0.00619D^2 - 0.00009D^3$	0.76	0.35	
				$W_2 = 0.35987 - 0.06403D - 0.02088H - 0.00006D^2H + 0.00830D^2 - 0.00011D^3$	0.79	0.33	
				$W_3 = 0.19827 + 0.00006D^2H$	0.69	0.39	
Stem ⩾10 cm	Wood	126.16	128.85	$W_1 = 22.37597 - 8.37187D + 0.74058D^2 - 0.00666D^3$	0.93	34.79	48
				$W_2 = -3.29612 - 3.04061D + 1.76383H + 0.01825D^2H + 0.05449D^2 - 0.00321D^3$	0.98	20.71	
				$W_3 = -5.09982 + 0.01354D^2H$	0.97	22.45	
	Bark	9.65	9.17	$W_1 = 2.53726 - 0.87814D + 0.07910D^2 - 0.00103D^3$	0.93	2.45	
				$W_2 = 2.31399 - 0.83330D + 0.01625H + 0.00016D^2H + 0.07321D^2 - 0.00100D^3$	0.93	2.48	
				$W_3 = 0.59597 + 0.00093D^2H$	0.91	2.76	
Stem <10 ⩾2 cm	Wood	5.92	3.15	$W_1 = -10.06115 + 3.52880D - 0.19265D^2 + 0.07297D^3$	0.70	1.77	60
				$W_2 = -10.61509 + 3.13036D + 0.34530H - 0.00028D^2H - 0.18311D^2 + 0.00304D^3$	0.72	1.75	
				$W_3 = 7.34995 - 0.00015D^2H$	0.19	2.85	
	Bark	0.82	0.38	$W_1 = -0.91638 + 0.39402D - 0.02183D^2 + 0.00034D^3$	0.63	0.24	
				$W_2 = -0.95329 + 0.36137D + 0.02666H - 0.00003D^2H - 0.02091D^2 + 0.00034D^3$	0.63	0.24	
				$W_3 = 0.99760 - 0.00002D^2H$	0.20	0.34	
Live branches ⩾2 cm	Wood	7.65	11.68	$W_1 = -0.27805 + 0.16935D - 0.02854D^2 + 0.00138D^3$	0.74	6.13	60
				$W_2 = 1.67559 - 1.80686D + 0.80548H - 0.00345D^2H + 0.09813D^2 + 0.00109D^3$	0.83	5.09	
				$W_3 = -1.88069 + 0.00098D^2H$	0.62	7.24	
	Bark	1.39	2.10	$W_1 = -0.14398 + 0.04494D - 0.00525D^2 + 0.00024D^3$	0.71	1.16	
				$W_2 = 0.13492 - 0.13952D + 0.05656H - 0.00036D^2H + 0.00820D^2 + 0.00020D^3$	0.74	1.11	
				$W_3 = -0.31857 + 0.00018D^2H$	0.62	1.30	

Table 4 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	7.90	8.00	$W_1 = -4.61136 + 1.24532D - 0.07189D^2 + 0.00171D^3$	0.87	3.01	60
			$W_2 = -3.31746 + 0.70269D + 0.07501H - 0.00128D^2H - 0.02432D^2 + 0.00153D^3$	0.91	2.57	
			$W_3 = 0.63355 + 0.00075D^2H$	0.77	3.86	
Living tree above ground without foliage[2]	165.76	159.05	$W_1 = 10.06313 - 4.11975D + 0.52630D^2 - 0.00127D^3$	0.96	33.17	
			$W_2 = -13.14671 - 1.65204D + 3.00210H + 0.01342D^2H + 0.01753D^2 + 0.00181D^3$	0.98	23.60	
			$W_3 = 2.98118 + 0.01679D^2H$	0.98	23.07	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 5. Equations for predicting biomass (kg) of trembling aspen

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	4.65	4.51	$W_1 = 0.75552 - 0.15590D + 0.01668D^2 - 0.00009D^3$	0.91	1.41	60
				$W_2 = 0.77114 - 0.08221D - 0.04291H + 0.00008D^2H + 0.01330D^2 - 0.00009D^3$	0.91	1.43	
				$W_3 = 0.45975 + 0.00039D^2H$	0.89	1.48	
	Bark	1.09	1.00	$W_1 = 0.04581 - 0.00460D + 0.00285D^2 - 0.00002D^3$	0.81	0.44	
				$W_2 = 0.12605 - 0.11412D + 0.04540H - 0.00014D^2H + 0.00932D^2 - 0.00005D^3$	0.83	0.43	
				$W_3 = 0.22553 + 0.00008D^2H$	0.76	0.49	
Stem ⩾10 cm	Wood	137.62	148.66	$W_1 = 33.51065 - 11.39066D + 0.90827D^2 - 0.00867D^3$	0.96	31.65	47
				$W_2 = 11.82721 + 3.84585D - 4.44792H + 0.02204D^2H - 0.13801D^2 - 0.00301D^3$	0.99	18.47	
				$W_3 = -7.12648 + 0.01344D^2H$	0.98	19.53	
	Bark	33.87	35.40	$W_1 = 9.17700 - 3.25483D + 0.26676D^2 - 0.00308D^3$	0.98	5.48	
				$W_2 = 6.68578 - 2.93800D + 0.26976H + 0.00092D^2H + 0.21662D^2 - 0.00261D^3$	0.98	5.25	
				$W_3 = -0.37347 + 0.00318D^2H$	0.97	6.14	
Stem <10 ⩾2 cm	Wood	5.50	3.33	$W_1 = -7.40326 + 3.04881D - 0.16770D^2 + 0.00255D^3$	0.68	1.93	60
				$W_2 = -8.82096 + 2.64054D + 0.47405H - 0.00014D^2H - 0.16747D^2 + 0.00275D^3$	0.74	1.78	
				$W_3 = 6.79602 - 0.00012D^2H$	0.16	3.09	
	Bark	1.91	0.84	$W_1 = -1.50444 + 0.63864D - 0.03004D^2 + 0.00041D^3$	0.60	0.54	
				$W_2 = -1.83311 + 0.51907D + 0.12347H - 0.00006D^2H - 0.02877D^2 + 0.00045D^3$	0.65	0.52	
				$W_3 = 1.97725 - 0.00001D^2H$	0.01	0.84	
Live branches ⩾2 cm	Wood	9.98	13.86	$W_1 = -5.59835 + 1.60027D - 0.11546D^2 + 0.00290D^3$	0.89	4.82	60
				$W_2 = -4.02389 + 1.55223D - 0.25338H - 0.00041D^2H - 0.09120D^2 + 0.00263D^3$	0.89	4.78	
				$W_3 = -2.06470 + 0.00112D^2H$	0.78	6.51	
	Bark	5.59	7.60	$W_1 = -2.04519 + 0.61455D - 0.04806D^2 + 0.00136D^3$	0.94	1.88	
				$W_2 = -1.05167 + 0.70571D - 0.22604H - 0.00012D^2H - 0.03869D^2 + 0.00120D^3$	0.95	1.81	
				$W_3 = -1.27097 + 0.00064D^2H$	0.84	3.03	

Table 5 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	6.45	6.99	$W_1 = -3.44449 + 1.02089D - 0.04982D^2 + 0.00102D^3$	0.56	4.77	60
			$W_2 = -1.41131 + 0.84009D - 0.26252H - 0.00066D^2H - 0.01269D^2 + 0.00065D^3$	0.60	4.62	
			$W_3 = 1.64445 + 0.00045D^2H$	0.49	5.03	
Living tree above ground without foliage[2]	206.73	211.32	$W_1 = 23.61521 - 7.88903D + 0.78372D^2 - 0.00362D^3$	0.98	33.36	60
			$W_2 = 2.39343 + 6.95977D - 4.31874H + 0.02150D^2H - 0.23719D^2 + 0.00192D^3$	0.99	22.12	
			$W_3 = 0.34961 + 0.01916D^2H$	0.99	22.43	

1 W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

2 Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 6. Equations for predicting biomass (kg) of alpine fir

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	5.03	4.77	$W_1 = -0.06765 + 0.08228D + 0.00034D^2 + 0.00024D^3$	0.93	1.29	60
				$W_2 = -0.05645 + 0.05788D + 0.02381H + 0.00002D^2H + 0.00025D^2 + 0.00024D^3$	0.93	1.31	
				$W_3 = 0.46113 + 0.00049D^2H$	0.92	1.34	
	Bark	0.91	0.87	$W_1 = -0.08094 + 0.01565D + 0.00099D^2 + 0.00001D^3$	0.81	0.39	
				$W_2 = -0.00809 - 0.01961D + 0.00677H - 0.00013D^2H + 0.00419D^2 + 0.00002D^3$	0.82	0.38	
				$W_3 = 0.14051 + 0.00008D^2H$	0.77	0.42	
Stem ⩾10 cm	Wood	98.22	99.26	$W_1 = 21.12527 - 7.68865D + 0.65238D^2 - 0.00659D^3$	0.97	16.13	45
				$W_2 = 11.92801 - 3.07443D - 1.04906H + 0.01553D^2H + 0.25317D^2 - 0.00780D^3$	0.99	9.17	
				$W_3 = -0.13154 + 0.01051D^2H$	0.99	12.03	
	Bark	17.05	17.61	$W_1 = 4.95439 - 1.67932D + 0.13444D^2 - 0.00150D^3$	0.95	4.09	
				$W_2 = 3.64546 - 0.92782D - 0.26303H + 0.00200D^2H + 0.08052D^2 - 0.00165D^3$	0.96	3.84	
				$W_3 = -0.07917 + 0.00183D^2H$	0.95	4.01	
Stem <10 ⩾2 cm	Wood	4.95	2.13	$W_1 = -2.62088 + 1.70328D - 0.09375D^2 + 0.00145D^3$	0.43	1.64	60
				$W_2 = -1.84770 + 0.90021D + 0.58614H - 0.00040D^2H - 0.07285D^2 + 0.00145D^3$	0.50	1.57	
				$W_3 = 5.54090 - 0.00006D^2H$	0.08	2.06	
	Bark	1.22	0.44	$W_1 = -0.35726 + 0.25257D - 0.01125D^2 + 0.00015D^3$	0.37	0.36	
				$W_2 = -0.05659 - 0.05016D + 0.21647H - 0.00018D^2H - 0.00283D^2 + 0.00015D^3$	0.56	0.31	
				$W_3 = 1.12484 + 0.00001D^2H$	0.04	0.44	
Live branches ⩾2 cm	Wood	3.76	6.68	$W_1 = 2.99468 - 0.68108D + 0.03213D^2 - 0.00011D^3$	0.59	4.36	60
				$W_2 = 3.80643 - 1.14394D + 0.15929H - 0.00125D^2H + 0.06567D^2 - 0.00002D^3$	0.62	4.33	
				$W_3 = -1.18169 + 0.00053D^2H$	0.55	4.52	
	Bark	1.45	2.44	$W_1 = 1.43616 - 0.34084D + 0.01785D^2 - 0.00015D^3$	0.63	1.52	
				$W_2 = 1.72883 - 0.50415D + 0.05315H - 0.00046D^2H + 0.03005D^2 - 0.00011D^3$	0.65	1.50	
				$W_3 = -0.42003 + 0.00020D^2H$	0.59	1.58	

Table 6 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	12.65	12.59	$W_1 = 3.66031 - 1.02312D + 0.09105D^2 - 0.00112D^3$	0.79	5.94	60
			$W_2 = 2.60440 - 0.18616D - 0.48891H + 0.00112D^2H + 0.05459D^2 - 0.00118D^3$	0.79	6.01	
			$W_3 = 1.57952 + 0.00118D^2H$	0.78	6.01	
Living tree above ground without foliage[2]	145.29	139.95	$W_1 = 31.11285 - 9.36280D + 0.82440D^2 - 0.00760D^3$	0.97	23.66	60
			$W_2 = 21.81342 - 4.95270D - 0.75442H + 0.01625D^2H + 0.41297D^2 - 0.00890D^3$	0.98	19.13	
			$W_3 = 7.08763 + 0.01477D^2H$	0.98	20.56	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 7. Equations for predicting biomass (kg) of lodgepole pine

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	5.88	5.38	$W_1 = -2.53037 + 0.59982D - 0.02542D^2 + 0.00065D^3$	0.93	1.48	60
				$W_2 = -2.71527 + 0.64985D - 0.00077H + 0.00013D^2H - 0.02957D^2 + 0.00065D^3$	0.93	1.49	
				$W_3 = 0.91276 + 0.00051D^2H$	0.91	1.60	
	Bark	0.51	0.41	$W_1 = 0.05563 - 0.00402D + 0.00148D^2 - 0.00001D^3$	0.84	0.17	
				$W_2 = 0.06776 + 0.00968D - 0.01124H + 0.00002D^2H + 0.00095D^2 - 0.00002D^3$	0.84	0.17	
				$W_3 = 0.15704 + 0.00004D^2H$	0.82	0.18	
Stem ⩾10 cm	Wood	132.08	139.33	$W_1 = 0.01641 - 2.93815D + 0.37200D^2 + 0.00053D^3$	0.97	26.19	48
				$W_2 = -23.14520 + 3.48564D - 0.20011H + 0.01668D^2H - 0.15468D^2 + 0.00010D^3$	0.99	15.52	
				$W_3 = -1.64012 + 0.01361D^2H$	0.99	15.94	
	Bark	10.35	10.31	$W_1 = 2.90715 - 0.93137D + 0.07902D^2 - 0.00094D^3$	0.92	3.01	
				$W_2 = 2.20414 - 0.86942D + 0.08237H + 0.00027D^2H + 0.06930D^2 - 0.00091D^3$	0.92	3.02	
				$W_3 = 0.90031 + 0.00096D^2H$	0.90	3.28	
Stem <10 ⩾2 cm	Wood	5.17	2.79	$W_1 = 0.51913 + 1.33337D - 0.07980D^2 + 0.00126D^3$	0.32	2.37	60
				$W_2 = -2.19651 + 0.62996D + 0.94504H - 0.00065D^2H - 0.07296D^2 + 0.00163D^3$	0.48	2.10	
				$W_3 = 6.30156 - 0.00012D^2H$	0.18	2.55	
	Bark	0.87	0.48	$W_1 = 0.50635 + 0.15243D - 0.01007D^2 + 0.00017D^3$	0.28	0.42	
				$W_2 = 0.08127 + 0.01663D + 0.16501H - 0.00015D^2H - 0.00779D^2 + 0.00023D^3$	0.42	0.38	
				$W_3 = 1.06175 - 0.00002D^2H$	0.18	0.44	
Live branches ⩾2 cm	Wood	3.62	5.45	$W_1 = -0.44694 + 0.07728D - 0.00724D^2 + 0.00044D^3$	0.71	3.00	60
				$W_2 = 0.93835 - 0.68423D + 0.26284H - 0.00167D^2H + 0.04202D^2 + 0.00057D^3$	0.82	2.43	
				$W_3 = -0.54311 + 0.00042D^2H$	0.63	3.36	
	Bark	0.91	1.39	$W_1 = 0.21589 - 0.05716D + 0.00305D^2 + 0.00002D^3$	0.65	0.85	
				$W_2 = 0.62953 - 0.28875D + 0.08128H - 0.00051D^2H + 0.01796D^2 + 0.00007D^3$	0.79	0.66	
				$W_3 = -0.09196 + 0.00010D^2H$	0.56	0.93	

Table 7 continued

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	5.74	5.65	$W_1 = -4.01971 + 0.83309D - 0.03450D^2 + 0.00074D^3$	0.77	2.81	60
			$W_2 = -2.79484 + 0.84095D - 0.22052H - 0.00026D^2H - 0.02301D^2 + 0.00066D^3$	0.78	2.77	
			$W_3 = 1.12444 + 0.00047D^2H$	0.72	3.04	
Living tree above ground without foliage[2]	165.19	163.50	$W_1 = -2.71219 - 0.93774D + 0.29884D^2 + 0.00285D^3$	0.97	26.55	60
			$W_2 = -26.91929 + 3.77558D + 1.12097H + 0.01385D^2H - 0.15742D^2 + 0.00297D^3$	0.99	18.29	
			$W_3 = 8.24948 + 0.01597D^2H$	0.99	18.45	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 8. Equations for predicting biomass (kg) of tamarack larch

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	7.50	6.81	$W_1 = -1.50900 + 0.44290D - 0.01647D^2 + 0.00061D^3$	0.94	1.69	60
				$W_2 = -1.98465 + 0.71405D - 0.09729H + 0.00037D^2H - 0.03349D^2 + 0.00073D^3$	0.94	1.71	
				$W_3 = 0.51423 + 0.00084D^2H$	0.93	1.87	
	Bark	0.71	0.58	$W_1 = -0.23080 + 0.07493D - 0.00338D^2 + 0.00008D^3$	0.90	0.19	
				$W_2 = -0.24259 + 0.10740D - 0.02194H + 0.00003D^2H - 0.00472D^2 + 0.00009D^3$	0.90	0.19	
				$W_3 = 0.12538 + 0.00007D^2H$	0.87	0.21	
Stem ⩾10 cm	Wood	99.74	95.52	$W_1 = 14.18120 - 5.65541D + 0.53977D^2 - 0.00496D^3$	0.97	17.03	47
				$W_2 = 3.27071 - 8.20881D + 4.42203H + 0.00190D^2H + 0.46142D^2 - 0.00321D^3$	0.98	15.71	
				$W_3 = -0.69645 + 0.01214D^2H$	0.97	16.05	
	Bark	9.43	8.61	$W_1 = 0.49037 - 0.35548D + 0.04579D^2 - 0.00048D^3$	0.95	1.97	
				$W_2 = -1.15533 + 0.10191D + 0.02801H + 0.00093D^2H + 0.00399D^2 - 0.00011D^3$	0.96	1.87	
				$W_3 = 0.46561 + 0.00108D^2H$	0.95	1.90	
Stem <10 ⩾2 cm	Wood	5.09	2.44	$W_1 = -4.28028 + 1.93247D - 0.10116D^2 + 0.00153D^3$	0.35	2.02	60
				$W_2 = -5.76827 + 1.68674D + 0.52534H + 0.00034D^2H - 0.11549D^2 + 0.00178D^3$	0.49	1.83	
				$W_3 = 5.21896 - 0.00002D^2H$	0.003	2.46	
	Bark	1.07	0.44	$W_1 = -0.68399 + 0.33983D - 0.01760D^2 + 0.00027D^3$	0.35	0.37	
				$W_2 = -0.93739 + 0.34864D + 0.05105H + 0.00010D^2H - 0.02184D^2 + 0.00032D^3$	0.43	0.35	
				$W_3 = 0.99505 + 0.00001D^2H$	0.03	0.44	
Live branches ⩾2 cm	Wood	11.16	15.79	$W_1 = 4.64610 - 1.12870D + 0.05406D^2 + 0.00016D^3$	0.77	7.83	60
				$W_2 = 6.04326 - 0.97131D - 0.43765H - 0.00037D^2H + 0.07013D^2 - 0.00008D^3$	0.77	7.93	
				$W_3 = -3.19201 + 0.00173D^2H$	0.73	8.33	
	Bark	2.85	4.06	$W_1 = 1.80962 - 0.44842D + 0.02430D^2 - 0.00015D^3$	0.73	2.18	
				$W_2 = 1.40206 + 0.11897D - 0.33748H + 0.00058D^2H - 0.00221D^2 + 0.0000002D^3$	0.73	2.20	
				$W_3 = -0.77607 + 0.00044D^2H$	0.71	2.23	

Table 8 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	13.32	11.67	$W_1 = -0.75634 + 0.25909D + 0.01317D^2 + 0.00018D^3$	0.84	4.74	60
			$W_2 = -5.38738 + 3.89644D - 1.70365H + 0.00441D^2H - 0.18806D^2 + 0.00152D^3$	0.88	4.30	
			$W_3 = 1.82902 + 0.00139D^2H$	0.85	4.51	
Living tree above ground without foliage[2]	150.91	138.48	$W_1 = 13.73306 - 4.54319D + 0.53870D^2 - 0.00275D^3$	0.98	19.88	60
			$W_2 = -4.71726 - 2.19912D + 2.42532H + 0.00830D^2H + 0.16916D^2 + 0.00104D^3$	0.98	18.08	
			$W_3 = 4.52582 + 0.01769D^2H$	0.98	18.41	

[1] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[2] Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 9. Equations for predicting biomass (kg) of balsam poplar

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	4.27	4.10	$W_1 = -0.68266 + 0.21929D - 0.00593D^2 + 0.00024D^3$	0.94	1.04	60
				$W_2 = -0.64957 + 0.09407D + 0.07594H - 0.00018D^2H + 0.00032D^2 + 0.00024D^3$	0.94	1.06	
				$W_3 = 0.50669 + 0.00037D^2H$	0.91	1.22	
	Bark	0.93	0.85	$W_1 = -0.09998 + 0.04164D - 0.00069D^2 + 0.00004D^3$	0.87	0.31	
				$W_2 = -0.06017 - 0.05219D + 0.05237H - 0.00015D^2H + 0.00447D^2 + 0.00003D^3$	0.89	0.30	
				$W_3 = 0.18149 + 0.00007D^2H$	0.83	0.35	
Stem ≥10 cm	Wood	92.33	93.70	$W_1 = 15.21310 - 6.47927D + 0.58870D^2 - 0.00639D^3$	0.96	19.38	46
				$W_2 = 9.44451 - 4.80184D + 0.59103H + 0.00890D^2H + 0.33457D^2 - 0.00611D^3$	0.97	15.73	
				$W_3 = 4.31462 + 0.00875D^2H$	0.96	19.87	
	Bark	20.76	21.40	$W_1 = 5.99339 - 2.16445D + 0.17537D^2 - 0.00214D^3$	0.93	5.75	
				$W_2 = 5.44871 - 2.72924D + 0.55211H + 0.00002D^2H + 0.18133D^2 - 0.00213D^3$	0.93	5.73	
				$W_3 = 1.29249 + 0.00194D^2H$	0.90	6.95	
Stem <10≥2 cm	Wood	4.47	2.48	$W_1 = -3.08937 + 1.43114D - 0.06490D^2 + 0.00084D^3$	0.54	1.72	60
				$W_2 = -3.33039 + 0.73939D + 0.54753H - 0.00049D^2H - 0.04397D^2 + 0.00083D^3$	0.63	1.57	
				$W_3 = 4.44671 + 0.000002D^2H$	0.0001	2.50	
	Bark	1.52	0.78	$W_1 = -0.71942 + 0.38855D - 0.01694D^2 + 0.00022D^3$	0.47	0.58	
				$W_2 = -0.81012 + 0.16250D + 0.18253H - 0.00015D^2H - 0.01048D^2 + 0.00022D^3$	0.58	0.53	
				$W_3 = 1.38841 + 0.00001D^2H$	0.03	0.77	
Live branches ≥2 cm	Wood	8.97	13.94	$W_1 = -4.56803 + 1.33332D - 0.0811D^2 + 0.00215D^3$	0.79	6.49	60
				$W_2 = -3.38790 + 0.64686D + 0.11468H - 0.00221D^2H - 0.02191D^2 + 0.00209D^3$	0.82	6.12	
				$W_3 = -1.90646 + 0.00108D^2H$	0.66	8.20	
	Bark	4.98	7.38	$W_1 = -1.68567 + 0.50460D - 0.03542D^2 + 0.00099D^3$	0.87	2.76	
				$W_2 = -1.38162 + 0.48123D - 0.07579H - 0.00040D^2H - 0.02471D^2 + 0.00097D^3$	0.87	2.74	
				$W_3 = -1.20587 + 0.00061D^2H$	0.76	3.65	

Table 9 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	8.51	8.56	$W_1 = -2.57311 + 0.88432D - 0.03824D^2 + 0.00088D^3$	0.77	4.24	60
			$W_2 = -1.34078 + 0.62679D - 0.19545H - 0.00179D^2H + 0.01187D^2 + 0.00082D^3$	0.85	3.49	
			$W_3 = 1.72898 + 0.00067D^2H$	0.68	4.89	
Living tree above ground without foliage[2]	146.78	143.83	$W_1 = 7.88378 - 3.84748D + 0.51417D^2 - 0.00319D^3$	0.97	24.01	60
			$W_2 = 4.02873 - 4.84860D + 1.85135H + 0.00354D^2H + 0.43221D^2 - 0.00304D^3$	0.98	23.14	
			$W_3 = 10.8106 + 0.01352D^2H$	0.97	25.87	

1 W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

2 Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

Table 10. Equations for predicting biomass (kg) of white birch

Tree component		Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Stump	Wood	7.33	6.64	$W_1 = 0.57645 - 0.14927D + 0.02506D^2 - 0.00021D^3$	0.94	1.69	60
				$W_2 = 0.52500 - 0.41753D + 0.13213H - 0.00072D^2H + 0.04527D^2 - 0.00020D^3$	0.95	1.59	
				$W_3 = 1.01973 + 0.00064D^2H$	0.90	2.09	
	Bark	1.03	0.90	$W_1 = -0.05388 + 0.02051D + 0.00139D^2 + 0.000002D^3$	0.87	0.33	
				$W_2 = -0.05699 + 0.01070D + 0.00558H - 0.00001D^2H + 0.00184D^2 + 0.000004D^3$	0.87	0.34	
				$W_3 = 0.20622 + 0.00008D^2H$	0.85	0.35	
Stem ≥10 cm	Wood	151.13	160.24	$W_1 = 17.11175 - 7.38214D + 0.68825D^2 - 0.00477D^3$	0.95	37.37	45
				$W_2 = 16.49696 - 8.27928D + 0.71258H + 0.00387D^2H + 0.65175D^2 - 0.00562D^3$	0.95	37.70	
				$W_3 = -4.62429 + 0.01576D^2H$	0.94	38.90	
	Bark	23.87	25.70	$W_1 = 0.26779 - 0.47537D + 0.06956D^2 - 0.00016D^3$	0.88	9.12	
				$W_2 = 0.24739 - 0.10526D - 0.12643H + 0.00228D^2H + 0.02020D^2 - 0.00035D^3$	0.89	8.98	
				$W_3 = -0.37062 + 0.00245D^2H$	0.89	8.69	
Stem <10 ≥2 cm	Wood	7.02	4.17	$W_1 = -5.08498 + 2.72375D - 0.14188D^2 + 0.00206D^3$	0.48	3.10	60
				$W_2 = -5.85060 + 0.43338D + 1.32766H - 0.00149D^2H - 0.04607D^2 + 0.00146D^3$	0.60	2.76	
				$W_3 = 7.79243 - 0.00008D^2H$	0.03	4.14	
	Bark	1.75	1.10	$W_1 = -1.23255 + 0.58084D - 0.02784D^2 + 0.00038D^3$	0.37	0.90	
				$W_2 = -1.35791 + 0.21637D + 0.21343H - 0.00019D^2H - 0.01342D^2 + 0.00028D^3$	0.41	0.89	
				$W_3 = 1.75297 - 0.000001D^2H$	0.00003	1.11	
Live branches ≥2 cm	Wood	28.75	36.85	$W_1 = 15.36863 - 4.99900D + 0.34525D^2 - 0.00429D^3$	0.76	18.65	60
				$W_2 = 15.17651 - 6.34861D + 0.62396H - 0.00455D^2H + 0.46260D^2 - 0.00415D^3$	0.77	18.48	
				$W_3 = -2.36577 + 0.00315D^2H$	0.71	19.97	
	Bark	9.20	11.83	$W_1 = 4.74506 - 1.52515D + 0.10365D^2 - 0.00123D^3$	0.77	5.78	
				$W_2 = 4.71674 - 1.58204D + 0.03867H + 0.00009D^2H + 0.10385D^2 - 0.00126D^3$	0.77	5.88	
				$W_3 = -1.08220 + 0.00104D^2H$	0.75	5.93	

Table 10 continued.

Tree component	Mean	Standard deviation	Equation[1]	R^2	Standard error of estimate	N
Live branches <2 cm	15.00	17.08	$W_1 = -1.56484 + 0.58238D - 0.02410D^2 + 0.00117D^3$	0.79	7.98	60
			$W_2 = -1.64617 - 0.06173D + 0.29145H - 0.00232D^2H + 0.03434D^2 + 0.00125D^3$	0.81	7.81	
			$W_3 = 0.14188 + 0.00150D^2H$	0.75	8.53	
Living tree above ground without foliage[2]	245.18	249.43	$W_1 = 30.26575 - 10.63240D + 1.03970D^2 - 0.00706D^3$	0.96	53.79	60
			$W_2 = 28.37893 - 16.15575D + 3.22648H - 0.00303D^2H + 1.26124D^2 - 0.00859D^3$	0.96	54.65	
			$W_3 = 2.54997 + 0.02455D^2H$	0.94	59.80	

1 W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

2 Coefficients are not additive because living tree above ground without foliage includes stem <2 cm.

their field conditions. Pie diagrams (Fig. 4) illustrate the proportion of stem and nonstem components in the total dry weight of biomass in the entire tree. The distribution of biomass in the stem or branches can be determined from the ratios obtained for each tree species. Confidence bands were plotted (Fig. 5) for the predicted individual and mean biomass dry weights for each species, based on the polynomial model.

Biomass prediction equations were also obtained for each province separately and are available on request.

DISCUSSION

The polynomial model (Model 1) based on D, D^2, and D^3 provides R^2 values ranging from 0.96 to 0.99 for the total aboveground tree dry weight biomass. This is noteworthy because the model is based on diameter measurement for a given species and the results are in agreement with those of Payandeh (1981) indicating that tree biomass is primarily a function of dbh.

The addition of another two terms, H and D^2H (Model 2), provides a slightly better fit with R^2 values ranging from 0.96 to 0.99. The distribution of R^2 values (Tables 1-10) for the polynomial model was: 0.96—two species, 0.97—three species, 0.98—four species, and 0.99—one species. After adding the two additional terms, the distribution changed to 0.96—one species, 0.98—five species, and 0.99—four species. There was a corresponding shift (decrease) in the standard errors of estimate after including the above-mentioned extra two terms in the model.

The model containing the D^2H term only (Model 3) shows R^2 values ranging from 0.94 to 0.99 for the total aboveground tree dry weight biomass. The distribution of R^2 values in this case was: 0.94—one species, 0.96—one species, 0.97—one species, 0.98—three species, and 0.99—four species. Similar trends are obvious from the standard errors of estimate. Obviously, Model 2, using five predictor variables based on different combinations of D and H, provided a better fit than the model using D^2H only (Model 3).

Tables 1-10 also show that some tree stem and nonstem component categories (such as stem <10 cm, live branches ⩾2 cm, and live branches <2 cm) are usually better predicted by either of the two multiple regression models (models 1 and 2) than by the linear model based on the D^2H predictor only (Model 3).

The standard least squares regression models are based on a number of assumptions, but as pointed out by Cunia (1979), "it is ordinarily understood, at least implicitly, that seldom if ever the ... assumptions are *strictly* fulfilled by random samples drawn from *finite populations*." The plotting of biomass data showed heterogeneity of variance, i.e., larger variance was noticed for large values of D, H, and D^2H than for small values. Use of logarithmic transformation or weighted regression could have taken care of such unequal scatter but was avoided in order to retain additivity as one of the criteria for the required prediction equations. This approach offered a practical compromise, and as Keeping (1966) suggests, even though the ordinary statistical tools (t-test and F-test) make several assumptions, "these tests do appear to be approximately valid in many cases, even for considerable departures from the assumed conditions (...they are 'robust')." Thus only the standard regression modeling approach using untransformed variables was used in the study.

For reasons mentioned earlier, prediction equations for tree biomass weights have leaned heavily toward using convenient transformations such as logarithms (Bella and De Franceschi 1978; Brown 1976; Duinker 1981; Johnstone 1970; Ker 1980; Koerper and Richardson 1980; Pastor and Bockheim 1981; Schlaegel 1975; Stanek and State 1978; Zavitkovski *et al.* 1981). Such transformations inadvertently introduce bias in the mean predicted values and need corrections for obtaining the unbiased estimates (Baskerville 1972; Meyer 1941). The equations presented in this report avoid the use of such transformations, thus providing direct estimates and obviating the need for corrections. Further, because the models obtained are additive they have the advantage of providing various combinations of predicted estimates by simply adding the existing coefficients in the prediction equations (Bella 1968; Kozak 1970). This is in line with the approach taken by other workers for similar reasons (Alemdag 1980 and 1981; Alemdag and Horton 1981; Crow and Laidly 1980; Johnstone and Peterson 1980).

The standard errors of the regression coefficients were also computed[6]. An examination of these values showed that the standard errors of coefficients were extremely low in all models for the entire tree aboveground biomass.

Total dry matter is a measure of the efficiency of an ecosystem for energy conversion. It also represents the total energy (solar) put into a given system (Newbould 1967). Thus ecologically similar vegetation areas are likely to show similar responses, in total dry matter production, to similar energy inputs within a region. The excellent fit obtained in the derived prediction equations for estimating the entire tree biomass of each species, even when pooled over three sampling sites in the three prairie provinces, shows that total biomass is one of the best available ecological indicators of an ecosystem under study.

Because of the excellent fit and the low standard errors of estimate and coefficients, the regional equations presented in the report can be used for predicting the tree biomass weights in ecologically similar areas in all three provinces. The only limitation, however, is that because the data for these equations were collected primarily from the central portions of the provinces, their application to the extreme northern or extreme southern areas would, at best, provide only first-approximation estimates.

CONCLUSIONS

The following conclusions can be drawn from the present study:

1. It is possible to obtain aboveground biomass weights of 10 prairie tree species by using simple measurements such as diameter at breast height and the total height of the tree. Such estimates are highly accurate for predicting the entire living tree biomass but decrease in accuracy for predicting the stem and nonstem component biomass weights separately. Within components, merchantable stem components are better predicted than the nonmerchantable components of the tree.

2. The best results were from the model $W = a_0 + a_1 D + a_2 H + a_3 D^2 H + a_4 D^2 + a_5 D^3$, but the polynomial model $W = a_0 + a_1 D + a_2 D^2 + a_3 D^3$ was nearly as good for estimating the entire tree biomass weight of the 10 tree species. This could be of considerable help when measurements on only one variable (dbh) are available for obtaining first-approximation biomass estimates of a forest stand. When the additional measurement of total height is also available, the estimates provided by the model $W = a_0 + a_1 D^2 H$ are nearly as good as those by the model containing all 5 predictor variables.

3. The regional equations are valid for application in the middle portions across the three prairie provinces; however, a slightly better fit may be possible by using individual province prediction equations. On the other hand, the coefficients of the regional equations are likely to have yielded more stable values, being based on a much larger number of samples than the individual province equations. This aspect will be explored and assessed in a proposed pilot project demonstrating the use of biomass equations to obtain biomass inventories for each province.

ACKNOWLEDGMENTS

The field data for this report were collected under an ENFOR contract by Woodlot Service (1978) Ltd. Appreciation is expressed for the laboratory analysis done by Stan Lux and other technicians at the Northern Forest Research Centre. Special thanks go

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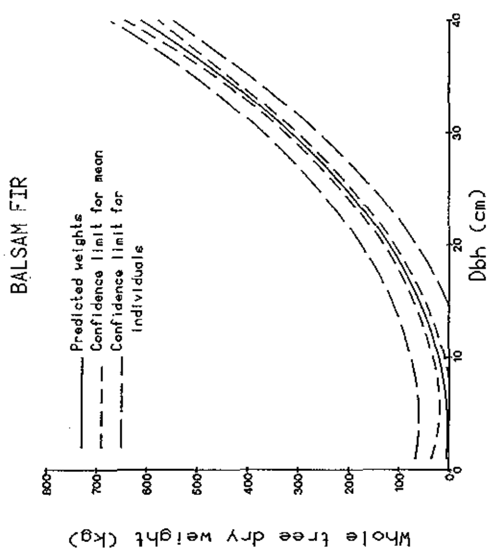
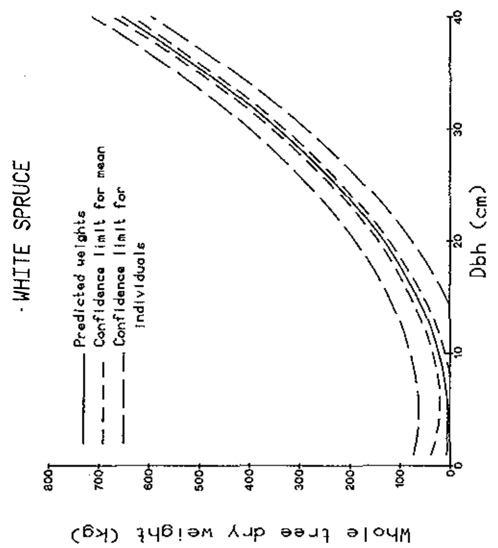
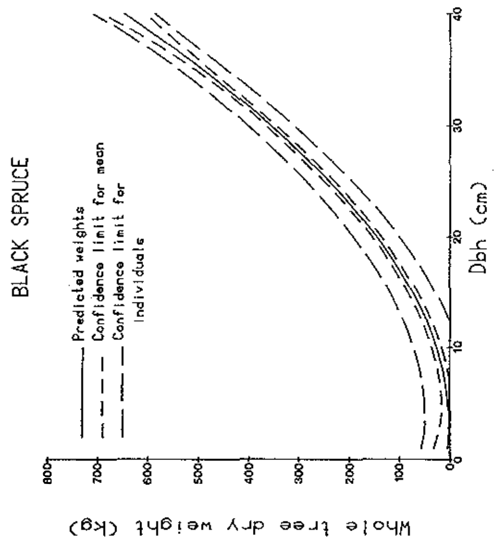
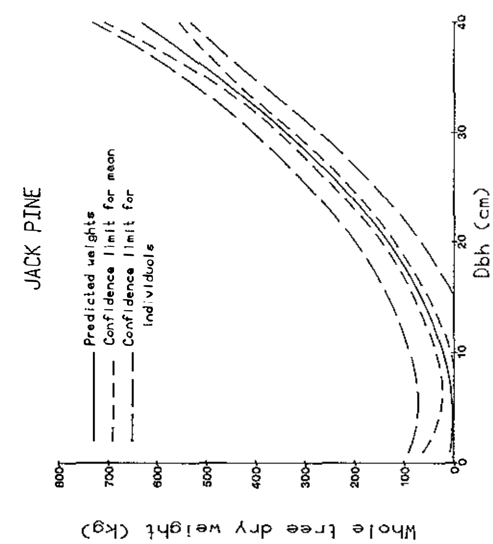
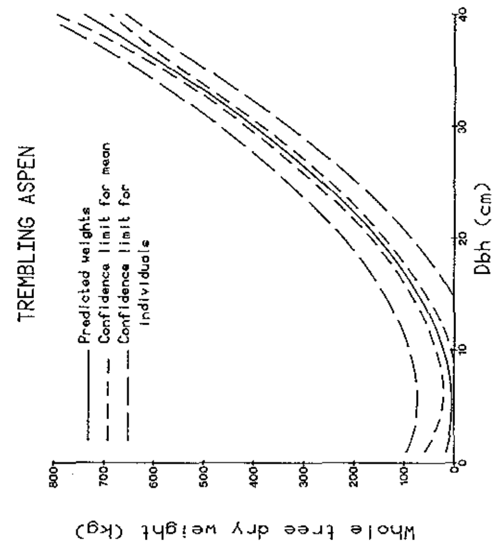
[6] These are on file and are available from the author.

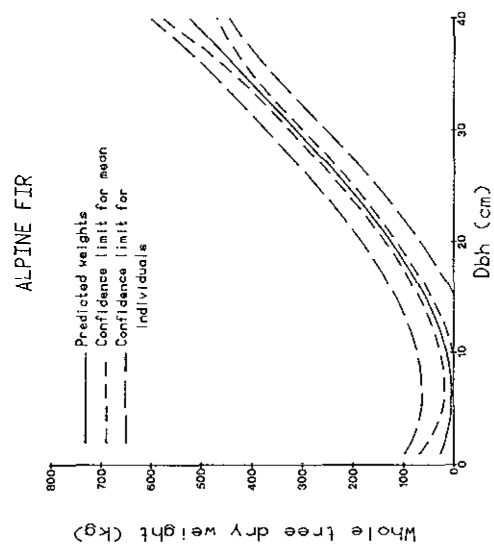

BALSAM FIR
Predicted weights
Confidence limit for mean
Confidence limit for individuals
Whole tree dry weight (kg)
Dbh (cm)


WHITE SPRUCE
Predicted weights
Confidence limit for mean
Confidence limit for individuals
Whole tree dry weight (kg)
Dbh (cm)


BLACK SPRUCE
Predicted weights
Confidence limit for mean
Confidence limit for individuals
Whole tree dry weight (kg)
Dbh (cm)


JACK PINE
Predicted weights
Confidence limit for mean
Confidence limit for individuals
Whole tree dry weight (kg)
Dbh (cm)


TREMBLING ASPEN
Predicted weights
Confidence limit for mean
Confidence limit for individuals
Whole tree dry weight (kg)
Dbh (cm)


ALPINE FIR
Predicted weights
Confidence limit for mean
Confidence limit for individuals
Whole tree dry weight (kg)
Dbh (cm)

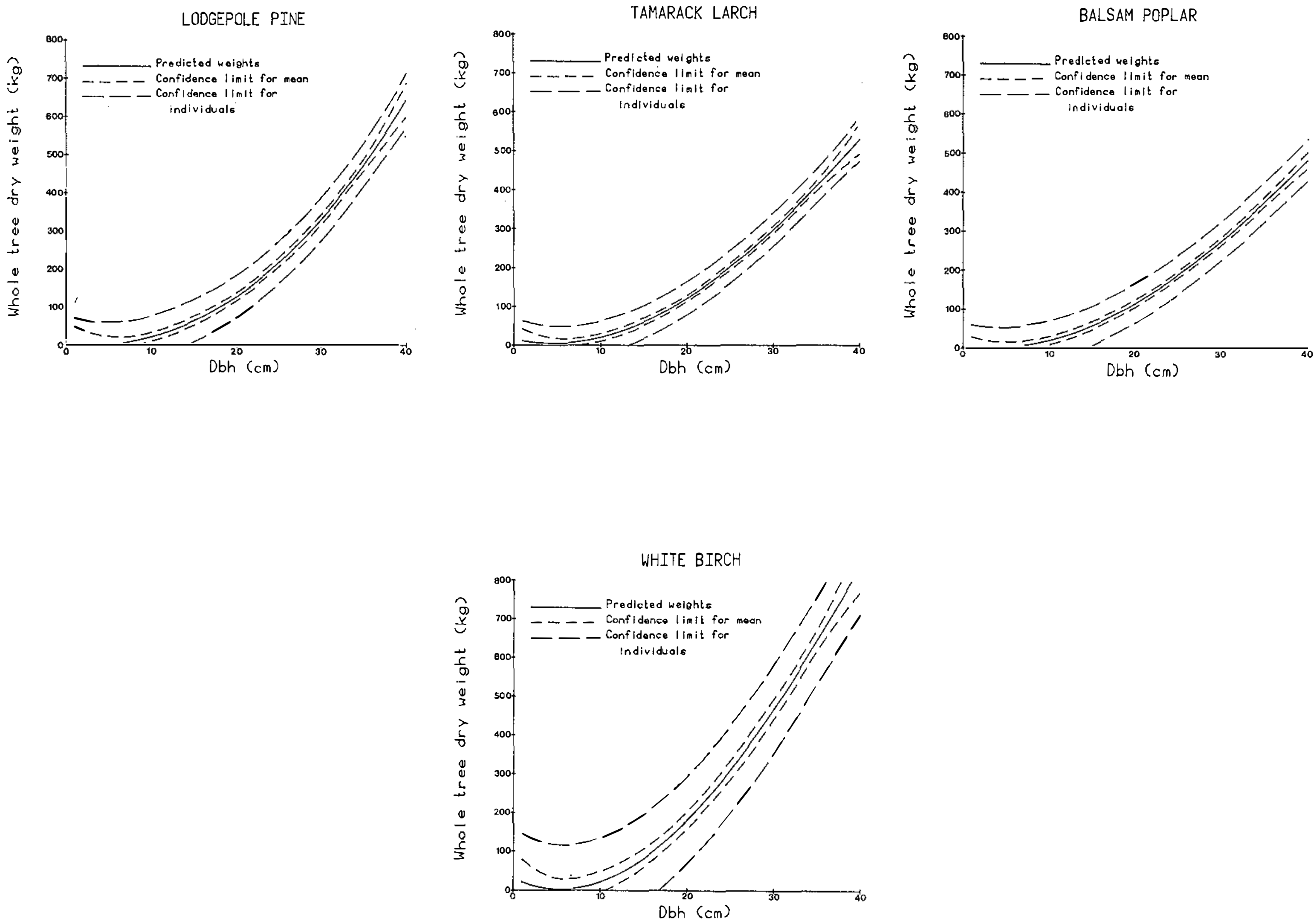
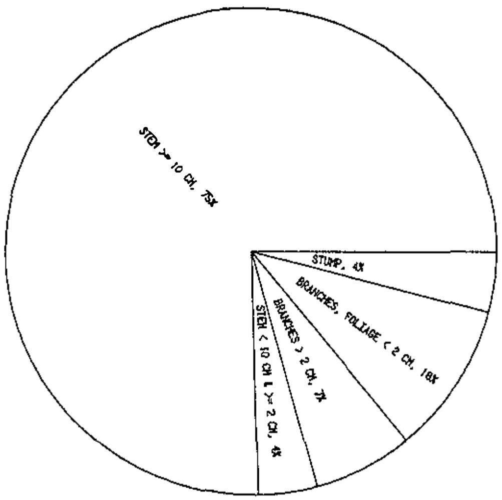
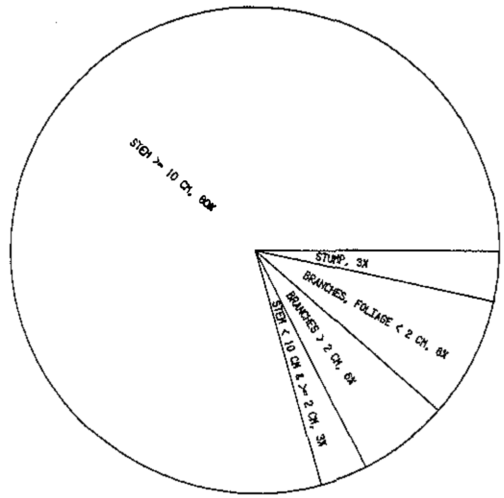


Figure 4. Component biomass dry weights of the 10 tree species.

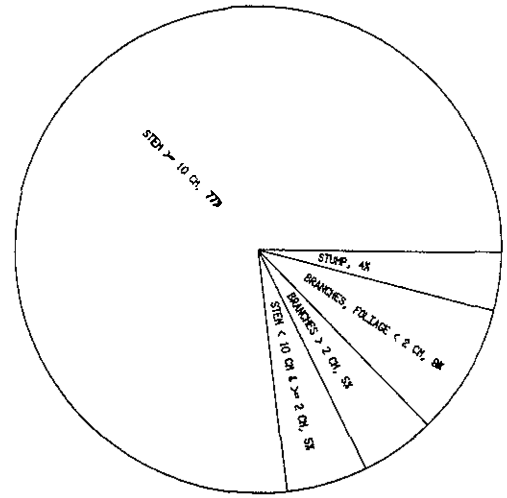
BALSAM FIR



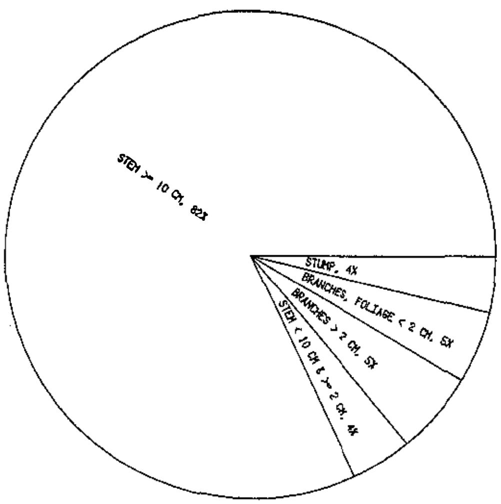
WHITE SPRUCE



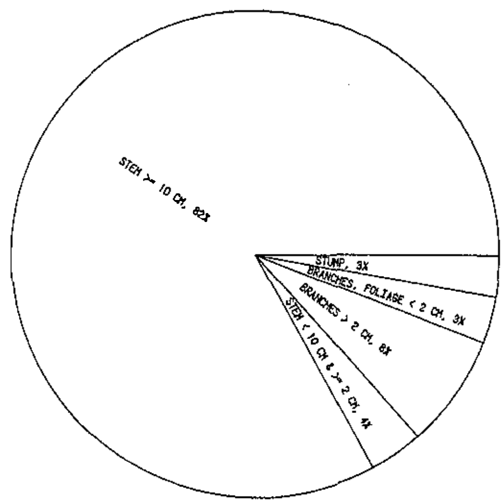
BLACK SPRUCE



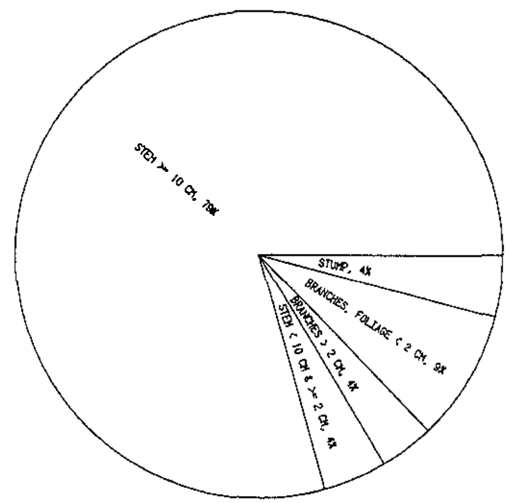
JACK PINE



TREMBLING ASPEN



ALPINE FIR



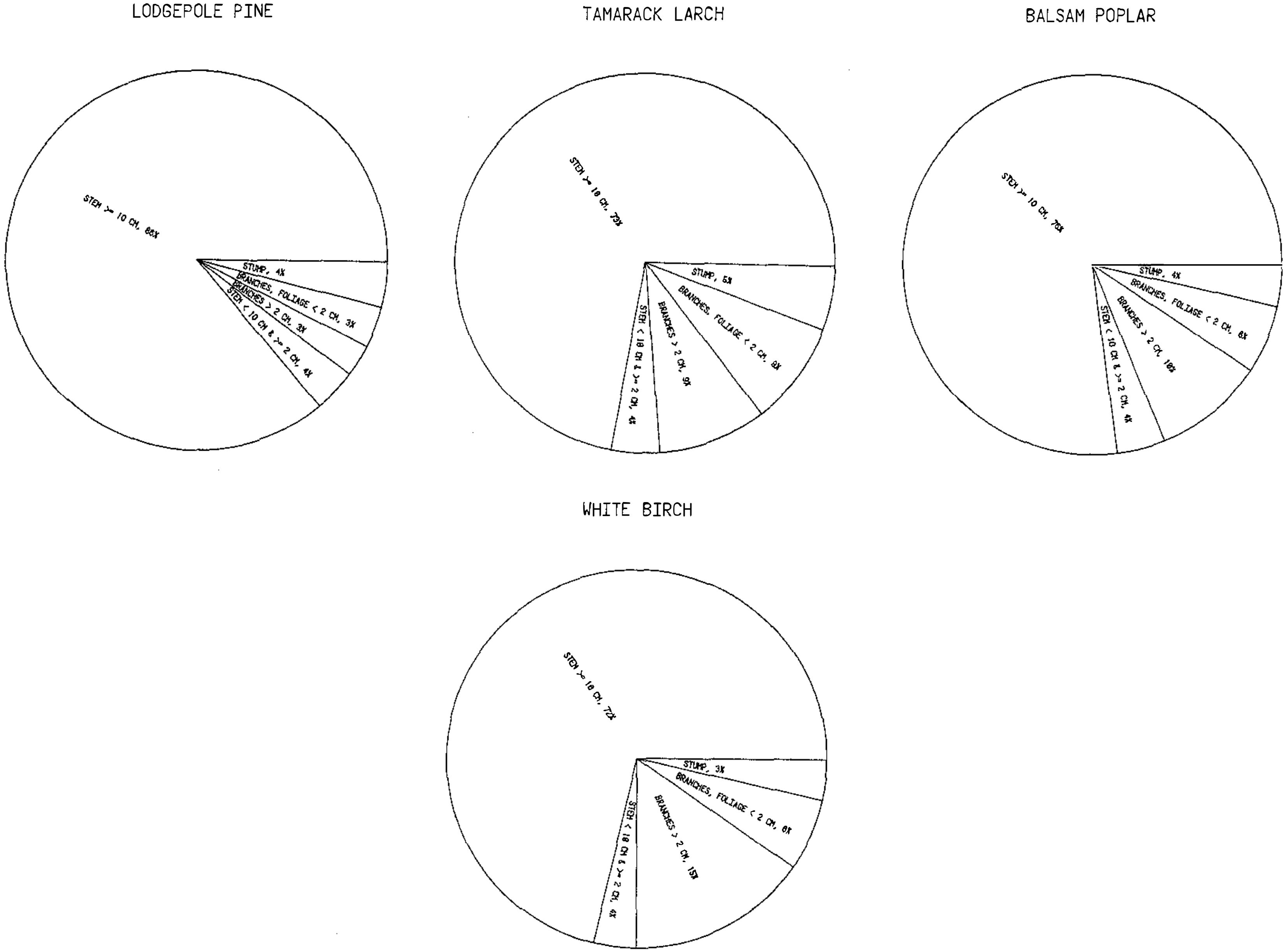


Figure 5. Confidence bands (95%) for the predicted mean and individual dry weight biomass of the entire tree above ground for the 10 tree species.

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